Enhanced Simulation Tools For the Synthesis of Fiber Bragg Grating in Optical Communication Systems

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Abstract— **In this paper, we are interested on simulation tools developing for designing optical component based on Fiber Bragg Grating (FBG), with potential uses in optical communication systems and sensors. Both principals for understanding and techniques for synthesizing fiber granting are emphasized. We focus on the two major applications, which are the design of Encoders/Decoders for optical access network based on OCDMA (Optical Code-Division Multiple Access) and compensation of chromatic dispersion. To ensure FBG reconstruction, we present an enhanced version of the two principal method of synthesizing: Layer Peeling method and genetic algorithm method. The first method is based on the Inverse Scattering problem resolution technique, the second method consists of optimizing a series of variables.**

Fiber Bragg Grating, synthesis method, Numérical tools, electromagnetic scattering inverse problems, layer peeling, genetic algorithm, optical code-division multiple access, chromatic dispersion.

I. Introduction

The accuracy of optical devices based on Fiber Bragg Grating (FBG) depends directly on the design process. For a well-known grating structure, the temporal and spectral behavior of the grating can be numerically determined using direct techniques [1]. However, in several important applications, the structure of the grating should be specified on basis of the desired reflection spectrum, known as a synthesis problem. In this article, we focus in the two important application of FBG tuned with the synthesis design process, which are the synthesis for OCDMA Encoders/Decoders and the synthesis of optical components based on FBG for chromatic dispersion compensation.

The performance of OCDMA systems is a very important issue considered on its viability, that could be considered as a potential technique for optical access network [2]. OCDMA techniques are grouped into three broad categories: direct-sequence (DS) [2], frequency encoding (FE) [3] and fast-frequency hopping (FFH) [4], where the based element for the encoder and the decoder could be a FBG, as they are readily fiber compatible. Working with conventional FBG to constitute DS-OCDMA or FE-OCDMA Encoder/Decoder, we fall often in considerable limitations. The disadvantages are multiple and could be misalignments impacts on the desired user signal power, the level of multi-access interference (MAI), and the bit error rate BER [5]. In order to surmount those limitations, convenient choice have to be carried out on the Encoder/Decoder profile based on FBG. In typical OCDMA communication system, chromatic dispersion does not affect seriously the system performance due to the low reach of optical access solution. However, in a long transmission system, the signal from the conventional receiver side is spread over time, due to the chromatic dispersion effect [6].

Depending on the application and the desired behavior, we choose the most convenient methods for synthesis, which can achieve the desired target characteristics. We use several adapted synthesis methods, which are flexible design process to introduce some constraints on: the temporal or spectral behavior, the physical parameters of the FBG and the format of the grating coupling coefficient.

To ensure FBG synthesis, we can distinguish two main families of algorithms that might be used, which are Electromagnetic Inverse Scattering (IS) [7] and genetic algorithm (GA) [8]. IS techniques offers a great flexibility in reconstruction the fiber Bragg grating and good accuracy depending on the used method [7,8]. These techniques are divided into three main methods: Fourier based methods [9-11], integral methods [12] and differential methods [13,14]. The Fourier based method uses the relation between the grating spectral response and the coupling coefficient. This method is valid only for grating having low reflectivity. Due to its approximation type, this synthesis approach is not applicable for the design of grating with high accuracy level. As second group of IS method, the integral method offers an exact solution to the synthesis problem. Within this approach, the scattering problem is expressed in terms of integral equations. The main inconvenient of this method is the complexity and difficulty involved in solving the equations. The differential method, as third group of IS exact algorithms, exploits fully the fiber grating medium, in which the wave propagated. Using this method, the medium is identified recursively layer by layer. This technique is also exact with appropriated complexity algorithm [15].

These methods are very useful techniques for solving the fiber Bragg grating synthesizing problem. Genetic algorithm, presents larger flexibility during the design process with flexibility in choosing the FBG characteristics. GA is probabilistic parallel search algorithm that follows the same principle as the nature evolution process [8]. Within this group of methods, the problem of synthesis is expressed as an optimizing problem.

The remainder of this paper is organized as follows. In section II, we present the two main synthesis techniques, differential methods as IS technique and genetic algorithm. We specify the advantages and the inconvenient of these techniques also a comparison between them. In Section III, we develop the design methodology that we use to achieve the desired characteristics of the synthesized FBG. In section IV, we illustrate several numerical simulations and applications of the FBG synthesis approach and the benefits in optical communications systems. Finally, in section V, we concluded by presenting the main results.

II. SYNTHESIS TECHNIQUES

In this section, we describe the two main synthesis methods: the Discreet Layer Peeling (DLP) [15] as differential method and the genetic algorithm based method. We limit our study to these two techniques due to their accuracy, flexibility on choosing the target spectral and temporal behavior and less complexity implementation [5,17].

A. Layer peeling method

The differential or direct method, are also referred as layer-peeling or dynamic deconvolution algorithm [15]. In the layer-peeling algorithm, the grating is divided into thin layers, each assumed to have a uniform profile as depicted in Fig. 1.

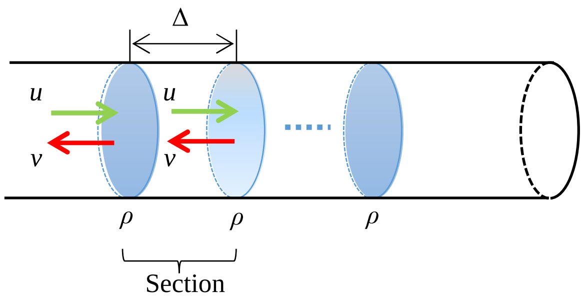


Figure 1. Discreet model of the DLP approach, *u* represents the forward-propagating fields, *v* represents the backward-propagating fields and *ρ* is a schematic representation of reflectors.

Thus, the medium is divided into *N* uniform sections, each with a length of Δ. The amplitude u_i and v_j are representing respectively the forward and backward propagating fields. Using the transfer matrix method, the fields of two consecutive sections are related by the transfer matrix *T*, which is defined by [8]:

$$T = T_{\Delta} T_{\rho}, \tag{1}$$

$$T_{\rho} = \left(1-|\rho|^2\right)^{-1/2} \begin{bmatrix} 1 & -\rho^* \\ -\rho & 1 \end{bmatrix}, \tag{2}$$

$$T_{\Delta} = \begin{bmatrix} \exp(i\delta\Delta) & 0 \\ 0 & \exp(-i\delta\Delta) \end{bmatrix}, \tag{3}$$

where δ is the wavenumber detuning compared the Bragg design wavenumber. Within the product of two matrices $T_{\Delta}T\rho$, TΔ represents the discrete reflector and T_{ρ} represents the pure propagation of the amplitude. The discrete complex reflection coefficient ρ, for each layer, is given by [15]:

$$\rho = -\tanh(|q|\Delta)\frac{q^*}{|q|}, \tag{4}$$

with *q* is the coupling coefficient. The problem of synthesis is to determine the series of N complex reflective amplitudes ρj, from the target reflection spectrum $r_1(\delta)$. At the level of the first section, the amplitude u_1 and v_1 at can be expressed by [15]:

$$\begin{bmatrix} u_1(\delta) \\ v_1(\delta) \end{bmatrix} = \begin{bmatrix} 1 \\ r_1(\delta) \end{bmatrix}. \tag{5}$$

In addition, at $t = 0$, we can consider the grating as only first reflector is present. Because at this time the light did not yet propagated to the other reflectors. Thus, we can compute ρ1 at $t = 0$ from the inverse Fourier transform of [15]:

$$r_1(\delta) = v_1(\delta)/u_1(\delta). \tag{6}$$

In the discrete version, this reflection coefficient, can obtained by the expression:

$$\rho_1 = \frac{1}{M}\sum_{m=1}^{M} r_1(m), \tag{7}$$

where $r_1(m)$ is the reflection spectrum of the target FBG and M is the number of wavelengths in the spectrum. As we know ρ_1, by the use of transfer matrix, we can propagate the fields to the next section. Moving to the next section, we have same conditions as in the first section, which is similar to the previous layer. Thus, we can use the same principals and estimation, to compute the reflection coefficient. This process will be repeated until all the amplitude reflectors ρ_j are calculated. The fields between two adjacent sections can be propagated by the transfer matrix, this transition is given in terms of the calculated reflection coefficient by [15]:

$$r_{j+1}(\delta) = \exp(-i2\delta\Delta)\frac{r_j(\delta)-\rho_j}{1-\rho_j^* r_j(\delta)}. \tag{8}$$

The refractive index modulation of the fiber Bragg grating is defined by [1]:

$$n(z) = n_0 + \Delta n(z)\cos\left(\frac{2\pi}{\Lambda} + \theta(z)\right), \qquad (9)$$

where z is the grating position, n0 is the refractive index, $\Delta n(z)$ is the refractive index modulation, $\theta(z)$ is the chirp parameter of the grating and Λ is the nominal period. The coupling coefficient can be formulated in function of these grating parameters by [8]:

$$q(z) = \frac{-i\pi}{2n_0\Lambda}\Delta n(z)\exp(-i\theta(z)). \qquad (10)$$

By applying the DLP algorithm to the target spectra, we are able to determine recursively the reflection coefficient of each layer, which leads to deduce the associated coupling coefficient and the index modulation $\Delta n(z)$, by using Eq. 10.

Since the grating length is a mandatary input parameter to the DLP algorithm, we can estimate its value from the target spectra, according to the following equation [16,17]:

$$L_{FBG} = \frac{\lambda_B^2}{n_0 \Delta\lambda_{FBG}}, \qquad (11)$$

where λ_B is the central Bragg wavelength and $\Delta\lambda_{FBG}$ is the bandwidth of the main lobe. The DLP algorithm as synthesis technique may be briefed in the following steps [7,18,19] :

- Step 1: start with the target spectrum $r_1(\delta)$, this spectrum must be physically realizable to guarantee the existence of a solution to the problem
- Step 2 : compute ρ_1 by the meaning of Eq. 7;
- Step 3 : propagating the fields using the transfer matrix, or directly from Eq. 10;
- Step 4: repeat step 2 until the whole grating is synthesize and the coupling coefficient and index modulation of the grating is determined.

If we consider *M* is the number of wavelengths of the discrete spectrum and *N* the number the layers constituting the grating structure, then the algorithm complexity will be of *O(MN)*. Depending on the accuracy of the solution needed and the number of the target spectrum wavelength, the value of *M* and *N* are choosed. However, the number of sample M of wavelength should be greater than or equal to the number of layer of the DLP algorithm, this leads to a minimum complexity of the algorithm of $O(N^2)$ [15].

B. *Genetic algorithm method*

In [20], Holland is the first to presents the principals of GA. GA is a probalistic parallel search algorithm based on natural behavior and selection. The GA represents an optimization method for function of several variables. There is a large variety of GA versions used for synthesizing FBG [8,21-23]. Depending on the application target and constraints, we choose two version of GA for FBG synthesis. The first version of the GA optimize the coupling coefficient directly of the grating. For the second version, we optimize directly the physical grating parameters. In both case, this optimization is made in conjunction with the transfer matrix method to calculate the values of the reflected and transmitted spectrum.

1) *Genetic Algorithm general principals*

The general process of GA method can be summarized as follow: an initial population is created randomly, this population represents possible values of the solution, and those values are combined and mutated to generate new values with better fitness to the target spectrum. These steps are repeated until the convergence of the algorithm is reached depending on the desired grating behavior and accuracy, as depicted in Fig. 2.

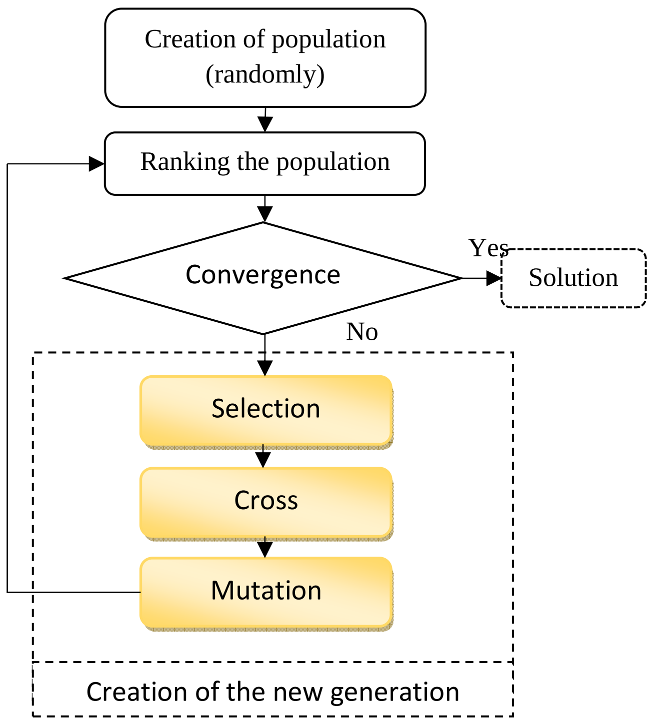


Figure 2. General schema of the Genetic Algorithm Pipeline.

The three main actions that lead the algorithm to convergence are:

- Selection: in this stage, only best elements of the population are allowed to move to the next generations,
- Cross: it allows the creation of the new generation base on the original population,

- Mutation: represents an important way to create diversity into the population. It introduces random change on population parameters. This procedure is useful to avoid a quickly falling into local minimum [8].

As selection criteria we use the probability of each individual to be selected in the cross process. This probability is defined by [22]:

$$PR_j = \frac{RW_j}{(1/\eta)\sum_j RW_j}, \tag{12}$$

where PR_j is the probability of next generation participation of the individual j $(j = 0,1,\ldots,\eta)$, η is the total number of the individual constituting the population and RW_j is the weight of the individual j. The individual, which present the best solution to the target behavior, is affected with a weight RW of $\eta\alpha$, where α is constant within the boundaries 1 to 1.5. The second-best individual receive a weight RW of $(\eta\text{-}1)\alpha$, and so on, until the individual with worst F is getting the weight of 1 [22]. During the cross step, for creating individual of the new generation, each two parents P1 and P2 will generate three individuals, described by [22]:

$$P_1, P_2 = \begin{cases} O_1 = 0.5P_1 + 0.5P_2 \\ O_2 = 1.5P_1 - 0.5P_2 \\ O_3 = -0.5P_1 + 1.5P_2 \end{cases}, \tag{13}$$

only the two elements from (O_1,O_2 and O_3) with the best fitness function value are selected for the next generation. Using this approach, the new individuals should have inherited the best parameters from the older generations and their solution should be closer to the target [8]. This schema has been demonstrated to converge slowly toward the best solution of the problem.

As mentioned before, the mutation process provides more variability on genetic algorithm and allow more diversity on new created generation. It consists on modifying randomly one selected parameter X with a probability mutation of Pm. The changes limits of the variable Xi are described by [22]:

$$X_i = \begin{cases} X_i + \varphi[Max(X_i) - X_i] \\ X_i + \varphi[X_i - Min(X_i)] \end{cases}, \tag{14}$$

where the function φ is expressed by [22]:

$$\varphi(y) = yr(1 - t/T)^{Bm}, \tag{15}$$

and where r is a random value within the boundaries 0 to 1, t is the current generation number, T is the maximum number of generations fixed for the execution of the algorithm and B is the mutation operator, that can be tuned for each different implementation of the GA. By using this mutation function definition, we notice that, as we are closer to the convergence, the mutation probability value decreases. This is explain the choose of this mutation function. In fact, for the last generations, the optimal solution should be reached and mutation process should not bring too many changes on the individual's parameters. During the first generations creation, the mutation values are higher, which permits to the algorithm to explore all possible parameters combinations. Thus, we avoid the quickly convergence of the algorithm to a local optimum and the global optimal solution can be reached.

In order to measure the convergence of an individual (as a possible solution) to the target spectrum and constraints, we define a cost-function F. This function measure the difference between the desired value of the spectrum and the calculated value. The aim of the genetic algorithm process is to minimize the performance value F and to ensure that we reach a global optimum solution.

As a cost-function, we choose to weight each part of the resulting spectrum differently, compared to the target spectrum. We select the cost-function expressed by [8]:

$$d\{R_c, R_t\} = \sum_j (R_{t,j}^w - R_{c,j}^w)^2, \tag{16}$$

where, R_C et R_t are respectively the calculated reflection spectrum and the target calculated spectrum, w is a weight parameter and j the index of the wavelength or detuning. By setting the weight parameter $w = 1$, the cost-function will be expressed as a quadratic error between the target and the calculated spectrum [17]. The performance of each individual is given as [22]:

$$\mathrm{F} = \sum_j (R_{t,j} - R_{c,j})^2. \tag{17}$$

2) GA synthesis using a predefined coupling coefficient function

Tremblay et al. in [21] propose to optimize a set of n weights am, instead of the entire coupling coefficient values. In this case, the coupling coefficient $q(z)$ is described as the square of a summation of cosine modes :

$$q(z) = AB\left[\sum_{m=1}^{n} a_m \cos\left(\frac{m\pi z}{L}\right)\right]^2, \tag{18}$$

where $-L/2 \leqslant z \leqslant L/2$, L is the total length of the grating, A = $q_{max} = \pi\Delta_{nmax}/\lambda_B$ with the maximal index modulation Δ_{nmax}, B is a constant value used for normalization purpose. Within this expression of the coupling coefficient, the shape is controlled and limiting the possible fluctuation on its behavior. The use of this predefined function, ensure that the coupling-coefficient function is all positive valued and remove all phase shift in the FBG. In this case, the designed FBG can fabricated with conventional techniques [21]. This method will be referenced in the remainder of this paper "GA-method1".

3) GA synthesis using FBG physical parameters

The second version of GA consists on finding directly the physical parameters of the grating achieving the target spectral and temporal behavior [22]. In this case, starting form only a given reflection spectrum of an FBG, we will find the optimized physical parameter (the grating length, the grating period, the refractive index modulation, phase shift if used and the chirp in the grating period). This second version of GA will be referenced in the remainder of this paper "GA-method2".

Both implementation of the two GA methods presented follow the same steps of implementation. The only major difference between the two variant is the parameters to be optimized. In the first case, we are looking for the coupling coefficient weight variables and in the second case, we are optimizing the fiber grating physical parameters directly [16].

III. Design Methodology

There is a large variety of application based on FBG, and the constraints imposed by each application differs largely. Fig. 3, represents the general schema of designing FBG regardless of the specified application.

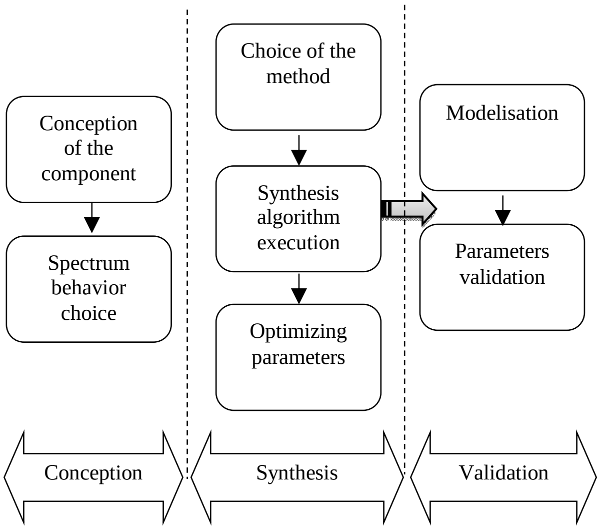


Figure 3. Example of a figure caption. (figure caption)

Our consolidated method of designing optical components for high speed communication systems based on FBG, consists of three main steps:

- Conception: During this phase, the general features of the component are defined. These characteristics are then convert to measurable parameters, as the spectral or temporal behavior with several constraints on the reflectivity.
- Synthesis and execution: based on the target spectrum and desired parameters we will choose the adapted method for synthesis and we will carry out the execution of the algorithm. For some case, several execution of the genetic algorithm is needed to optimize the algorithm variables and to ensure that we reach the optimized parameters.
- Validation and tuning: To validate the results we usually proceed with a modeling process with resulting parameters of FGB and an integration within optical system simulator to validate both the synthesis approach and the choices made in conception stage. This cycle, can repeated from conception for tuning the components characteristics.

IV. Simulations and Applications

In this section, we will demonstrate the design of OCDMA Encoder/Decoder and chromatic dispersion compensation using synthesis techniques of FBG. We will show the benefit of using the synthesis method as design tools for these optical components. First, we will demonstrate the synthesis of DS-OCDMA encoder, then Spectral Phase Encoding OCDMA (SPE-OCDMA) encoder and finally a flat-top filter with second order chromatic dispersion compensation.

A. DS-OCDMA Encoder/Decoder synthesis

As the first application example, we will enhance the spectral efficiency of DS-OCDMA by reducing the crosstalk coming from adjacent CDMA users. To achieve these characteristics we have opt to use a super-Gaussian spectrum profile having near-rectangular spectrum instead of using a uniform Bragg grating as mentioned in [11]. The super-Gaussian spectrum will reduce the Full Width Half-Maximum (FWHM) of the spectrum, eliminate inconvenient side lobes with a large flat-top band. We choose to implement a Prime sequence (PS) code having a length of 9 chips, which is able to multiplex up to 3 different users with a weight of 3.

We are interested in synthesizing superstructure-FBG composed by a three FBGs at the working wavelength of 1551 nm and the flat-top band of 1 nm. The maximal reflectivity of these FBG is set to (R_1 = 16%, R_2 = 24% and R_3 = 34%) [17]. The design of this SS-FBG permit to obtain an ideal code sequences with almost equal optical power pulses reflected from the DS-OCDMA encoder/decoder. In next paragraph we ensure the synthesis of the FBG3 using three different synthesis methods : DLP, GA with the coupling coefficient defined as series of square cosine modes and the real-coded genetic algorithm.

1) Synthesis using DLP method

As first numerical example demonstration, we synthesized the FBG_3 using the DLP method. The simulation results are shown in Fig. 4(a) and Fig. 4(b).

In this figure, we illustrate the real part of the coupling coefficient and the corresponding refractive index modulation as result of the synthesis process. The total length of the grating was estimated according to Eq. 11 and the refractive index modulation can be deduced from the coupling coefficient using Eq. 10. The number of layer used was *N= 70* and the number of the spectrum samples *M = 6000* for a working bandwidth of 4 nm.

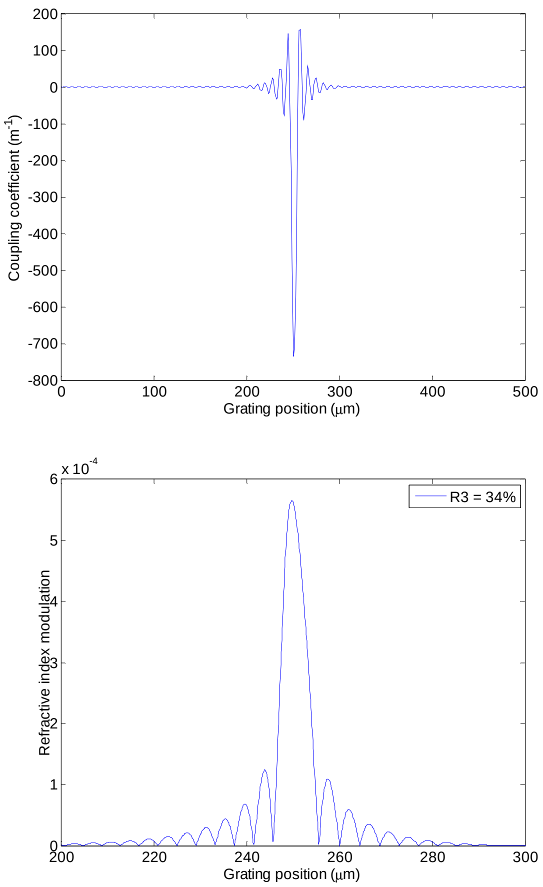


Figure 4. Plot of the real coupling coefficient of the FBG3, profile reconstructed using DLP method from Gaussian spectrum (a) and the corresponding refractive index modulation (b)

Fig. 5, shows the reflection spectrum of the synthesized grating compared to the target spectrum. From the graph, we can clearly notice the flat-top filter at -4.6dB for a bandwidth of 1nm. The same approach has been made of the other two grating with the corresponding maximum reflectivity values, which leads to the reconstruction of the whole SS-FBG.

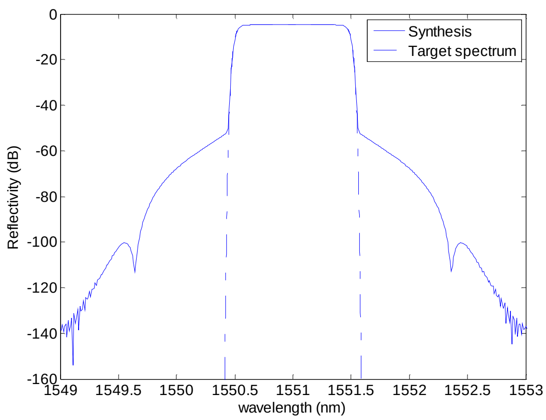


Figure 5. The synthesized reflection spectrum of FBG3 using DLP, with Gaussian profile as target input spectrum.

2) Synthesis using GA-method1

In order to compare the accuracy and the complexity of the DLP and the GA methods, we simulate the same target spectrum of the some Encoder using GA-method1. We choose the first case of implementation of the GA, in which the coupling coefficient follow the square of Fourier series as mentioned in Eq. 18. In this configuration, we have to determine the variables am, instead of optimizing the whole coupling coefficient values.

Fig. 6(a) and Fig. 6(a), shows respectively the coupling coefficient synthesis convergence by genetic algorithm and the corresponding refractive index modulation of the best result obtained after 300 generations. We notice that the coupling coefficient exhibit positive values with noticeable less fluctuations, which is a direct result of using a square Fourier series in the coupling coefficient expression. As the DLP method, the strength of the coupling coefficient is almost in the same amplitude range.

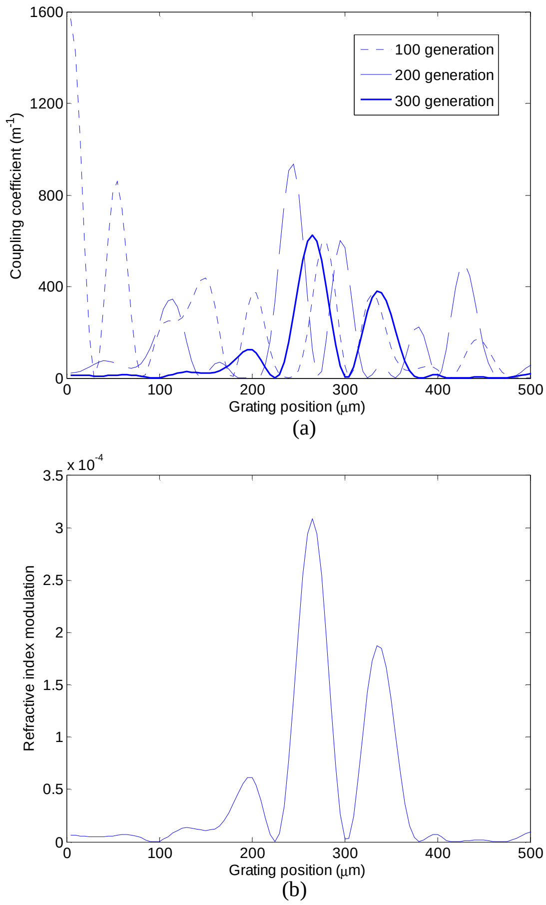


Figure 6. The synthesized coupling coefficient convergence, using Genetic algorithm as synthesis method (a) and the refractive index modulation of the solution (b).

Fig. 7, illustrate the comparison between the target and the calculated spectrum in the working bandwidth. We notice the presence of fluctuation within the main lobe and side lobes.

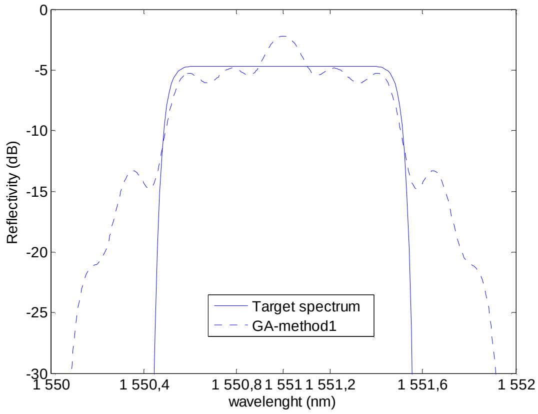


Figure 7. The ideal flat-top target spectrum and the calculated spectrum by the GA where the coupling coefficient is set as a some of square cosine modes fro FBG3.

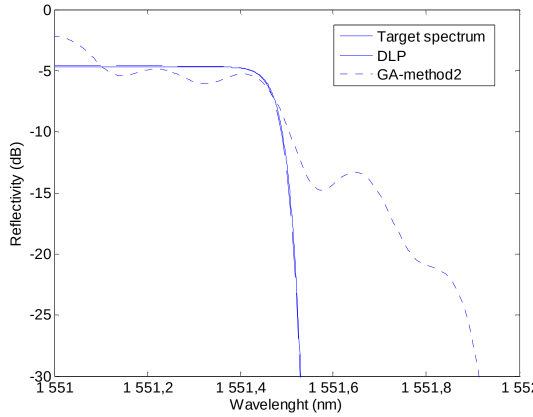


Figure 8. The ideal flat-top target spectrum and the calculated spectrum by the GA and DLP method for FBG3.

The values of the cost-function F, depending on the number of generation passed, is depicted in Table 1. We choose as a cost-function the quadratic error between the calculated and the target spectrum as mentioned in Eq .17. We notice that during the first iterations, the cost-function is decreasing as long as the execution of the algorithm continue, and it reaches its minimum from the generation t = 287.

TABLE I. COST-FUNCTION EXPRESSED IN TERM OF NUMBER OF GENERATION.

Number of generation (t)	Cost-function (F)
1	$1.16\ 10^{5}$
100	$4.54\ 10^{3}$
200	$7.38\ 10^{2}$
300	5.21

3) DLP method and GA with a predefined coupling coefficient function comparison

We observe that the DLP method is an exact method, but we did not have many control choice on results parameters, which may cause problem during the fabrication process. However, in GA method, we can introduce some constraint, but the results accuracy was less than those of the DLP method. The two spectrum of the synthesized grating by the DLP and GA-method1 are compared to the target spectrum in Fig.8.

To ensure the synthesis of DS-OCDMA Encoders/decoders, we opt for the GA-method1, which optimize directly the coupling coefficient of the grating, because the GA-method2 with its standard version is not applicable in this case. In fact, we design DS-OCDMA Encoder with ideal rectangular target spectrum reflectivity, which leads to the use of apodized FGB. The apodization function profile and parameters could not be calculated based on the GA-method2, as described in [22]. In next paragraph, we present an improved version of GA-method to ensure the synthesis of SPE-OCDMA Encoders/Decoders.

B. *SPE-OCDMA encoder/decoder synthesis*

In this section, we present the synthesis method, as a tool for designing SPE-OCDMA. In this case, we use also the two techniques DLP and GA to perform the synthesis running. We are interested on synthesizing SPE-OCDMA Encoder based on super-structured FBGs (SS-FBG) with step chirped profile [10]. This is an original an application of synthesis by using our enhanced genetic algorithm to reconstruct the physical grating parameter directly.

1) Synthesis with adapted GA-method2

To allow the synthesis of SPE-OCDMA Encoders/Decoders, we improved the GA algorithm by including three variables as result output: the number of grating sections constituting the whole grating, the phase shift array between adjacent sections and the chirp introduced between sub-gratings. Furthermore, we have to determine the basics parameters of the grating: the length L, the index modulation $\Delta n(z)$ and the central Bragg wavelength λ_B. As result, the total number of parameters to be optimized is set to six. In table 2, is depicted the optimized GA parameters used for the synthesis of SPE-OCDMA Encoder/Decoder.

TABLE II. PARAMETERS OF THE GENETIC ALGORITHM.

Grating parameters	Value
Weight (a)	1.1
Mutation Operator (Bm)	2.0
Probability of reproduction pc	45%
Probability of mutation pm	15%
Number of generation	300
Population (η)	75

As the number of the population size must be at least six to seven times more than the number of variables, a minimum population size of 45 individuals is needed [15]. However, the highly nonlinear nature of the problem obliges a much bigger population size, the value of 75 has been used in our simulation case.

We have considered a target spectrum for walsh-hadamard code. As the first simulation example, we use adapted real-coded genetic algorithm to synthesis the whole grating composed of an undefined sub-gratings. Fig. 9, represents a comparison between the desired spectrum and the calculated spectrum by the mean of GA.

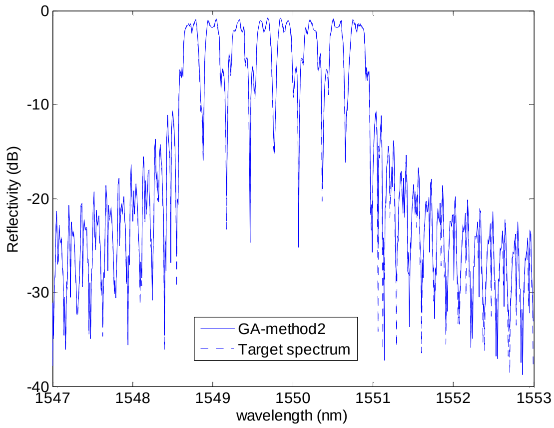


Figure 9. Target encoder spectrum (solid line) compared to the synthesis spectrum by the adapted GA (dashed line).

As we can notice, the algorithm convergence is almost exact in the main bandwidth, which represents the code information. However, very small discordance in sides lobes were visible and they are not affecting the performance of the encoder. Simulation synthesis outputs are shown in Table 3. The total length of the superstructure (SS-FBG) is L = 2.2cm. The target spectrum is achieved by the mean of 8 sections of FBGs, which means that each sub-grating has a length of L_{sub} = 2750µm. The refractive index modulation is uniform along the total superstructure and has the value of $\Delta n = 2.11\text{x}10^{-4}$. The central Bragg wavelength of the first uniform section is equal to λ_B = 1548.6 nm (or a grating period of Λ = 53.4µm). The chirp in terms of wavelength between two adjacent grating is Δλ = 0.3nm (or $\Delta\Lambda = 1.03x10^{-4}\mu m$ expressed in terms of nominal period). The phase shift array defined by $P= (0\ \pi\ 0\ \pi\ 0\ \pi\ 0)$, where the value of zero means that there is no phase shift.

TABLE III. SYNTHESIS PARAMETERS OF THE SPE-OCDMA ENCODER BY GA-METHOD2.

Grating parameters	Value
Total bragg grating length (L)	2.2 cm
Number of sub-gratings	8
Index modulation	$2.11\text{x}10^{-4}$
Bragg wavelength	1548.6nm
Chirp between section	0.3 nm
π - phase array	(0 π 0 π 0 π 0)
Spectre fitness	0.45

We observe that refractive index modulation presents a weak value, but the reflectivity reach 90% ; this is can explained by the considerable length of the total superstructure. We observe also, three thin windows on transmission that exists on the reflection spectrum of the SS-FBG, these corresponds to the three phase shifts detected by the synthesis process.

2) Comparison between DLP and GA-method2

In order to compare the accuracy and the convergence of the two techniques DLP algorithm to the GA-method2, we proceed to the synthesis of one single sub-grating of the SPE-OCDMA Encoder studied above by both method. In Fig. 10, is illustrated the comparison between the target spectrum of the sub-granting and the synthesis spectrum by DLP and GA-method2. In this simulation, we use the DLP configuration, with N = 70 and M = 250 and GA-method2 with standard output parameters. We can notice that both techniques represents good accuracy results. The synthesis spectrum fit almost exactly the target spectrum for the total working bandwidth.

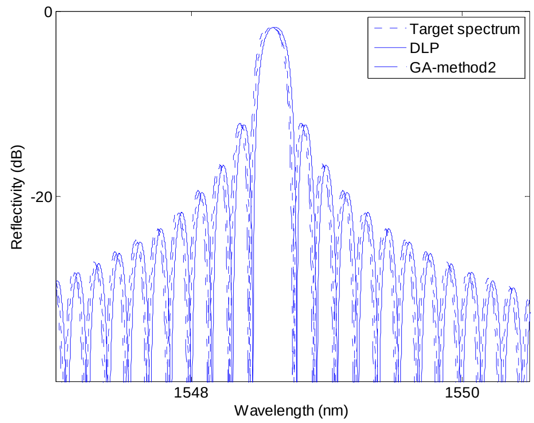


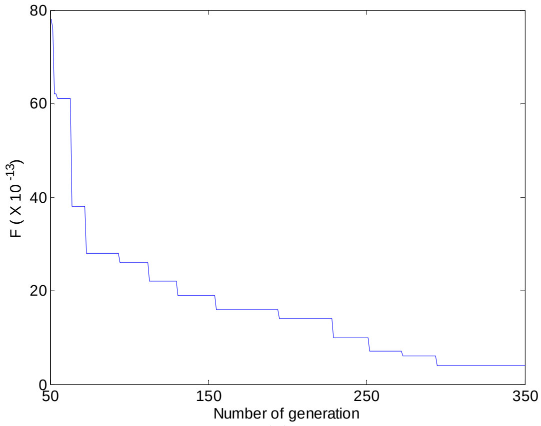
Figure 10. The Target Sub-grating spectrum (dot line), DLP (solid line) and the adapted GA-method2 (dashed line).

The resulted physical parameters from the synthesis process, for both methods, are shown in Table 4. The results outputs confirm the good accuracy of these two methods to synthesis uniform gratings. This is confirmed by the value of the cost-function that measure the error between the two gratings, this cost-value is very small.

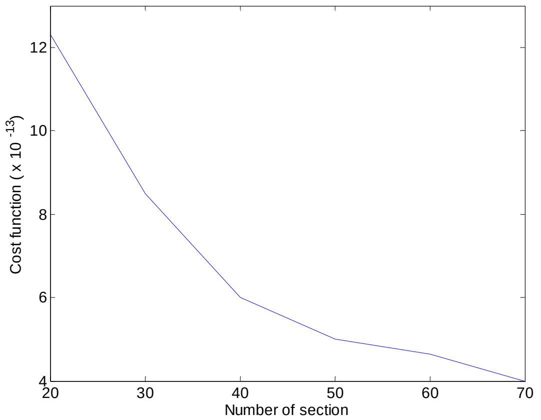
TABLE IV. OUTPUT PARAMETERS OF THE DLP AND REAL-CODED GA.

Grating parameters	DLP	GA-method2
Bragg grating length (L)	Given	5397µm
Index modulation	$1.05\text{x}10^{-4}$	$1.06\text{x}10^{-4}$
Bragg wavelength	1548.6 nm	1548.6 nm
Spectra fitness	~4 $\text{x}10^{-12}$	~4.5$\text{x}10^{-12}$

With these simulations, we demonstrate the accuracy of the DLP method and the flexibility of the GA for the synthesis of SPE-OCDMA encoder/decoder. We demonstrate that our adapted GA is more suited for the design of such complex optical component. In Fig. 11 (a) and (b), we illustrate respectively the cost-function (convergence fitness) of the DLP based on the number of layers used and the GA in terms of the number generations.



(a)



(b)

Figure 11. Real-coded genetic algorithm convergence (cost-function F) in terms of the number of generation (a), DLP fitness as function of the number of layers used (b).

To ensure the synthesis of SPE-OCDMA Encoders/decoders, we present a new version of the GA able to synthesis a target tunable spectrum based on SS-FBG. The use of a direct method is also possible to synthesis this type of components, but as in DS-OCDMA case, we do not have any control on the coupling coefficient behavior and physical parameters, which leads to complicate fabrication constraints. In our case, we are able to design SPE-OCDMA Encoder/Decoder based on FBGs with uniform index modulation, which can be fabricated with conventional techniques.

C. Chromatic dispersion compensation

In this section, we will demonstrate the efficiency of the synthesis techniques for design optical components based on FBG for chromatic dispersion compensation. Dispersion is one of the most limitations on data bit rates, fiber length and optical source spectral width [6]. It is caused by the pulse broadening, while propagating through the fiber. It becomes a problem when the optical pulses overlap in the transport fiber. In Fig. 12, we present the typical schema of chromatic dispersion compensation using chirped FBG.

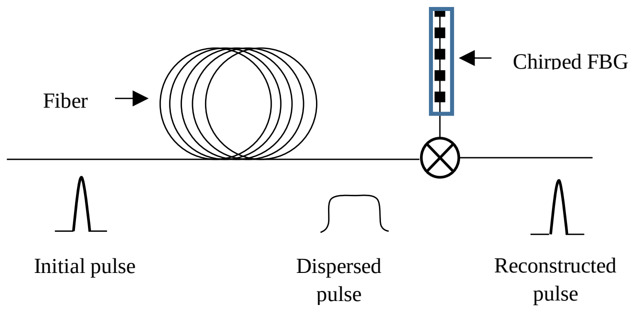


Figure 12. Chromatic dispersion illustration and compensation using chirped FBG.

To ensure second-order dispersion compensation using fiber grating, we consider the target spectrum as Gaussian profile with the phase defined as [15]:

$$r(\delta)=\sqrt{R}\left[-\frac{\delta}{\delta_{PB}}\right]\exp\left[-i\beta_2 L_F (c\delta/n)^2/2\right], \quad (19)$$

where R is the maximum reflectivity, δ_{PB} represents the filter bandwidth expressed in term of detuning, β_2 is the second-order dispersion coefficient, L_F is the fiber length, c is the speed of light and n is the refractive index modulation. In Fig. 13 and Fig. 14, we illustrate respectively the component reflection spectrum and the real part of the coupling coefficient of the synthesized grating with flat-top filter and second order dispersion compensation using DLP approach.

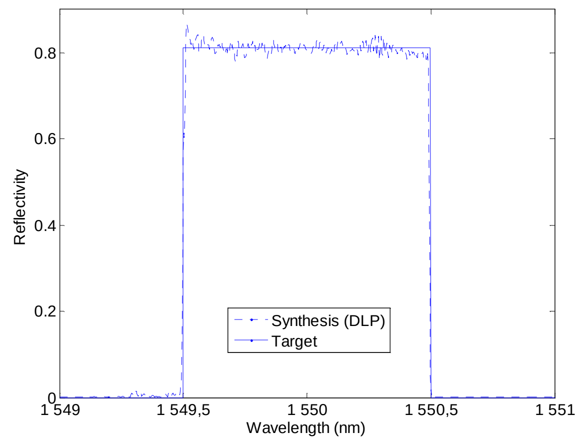


Figure 13. Reflection spectrum compared to the target spectrum.

We can notice that the target flat-top window of 1 nm fit the calculated spectrum, we Remarque also the existence of small fluctuation in the main bandwidth as depicted in Fig. 13(a). These fluctuation are very small and did not affect the component characteristics.

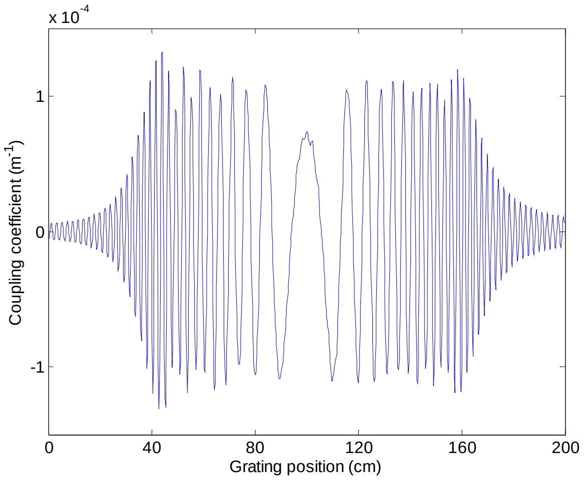


Figure 14. Real part of the coupling coefficient resulting from the synthesis process of a flat-top filter with second-order dispersion compensation.

As simulation technique, we choose for the DLP algorithm. We choose this method due to its exactitude and because the relation between the chromatic dispersion parameters and the spectrum reflectivity is expressed by function Eq. 19. Thus, the reconstruction and identification process might be achieved by a direct method. For this example, the grating Length was fixed to 200 cm, as input parameter for the DLP algorithm, and the number of layers N = 500 with the number of wavelengths of M = 6000.

For this simulation case, we consider the compensation filter with parameter described in Table 5. Within these parameters, the synthesized grating is an ideal reflection filter at the wavelength of 1550nm for a bandwidth of 0.54nm, also this grating will be able to compensate the chromatic dispersion (D=17 ps/nm-km) at this wavelength for a total transport fiber of 30km.

TABLE V. SECOND-ORDER DISPERSION FILTER COMPENSATION PARAMETERS..

Grating parameters	Value
Maximum reflectivity : R	0.8
Filter bandwidth : δ_{PB}	0.54 nm
Dispersion coefficient : β_2	-21.7 ps^2/km
Fiber length : L_F	30 km

Besides we choose a direct an exact method to synthesis, we calculated the quadratic error between the target spectrum and the calculated one using Eq. 19. The value of this error is 1.45, this value reflect the good accuracy of the DLP method for this kind of application.

As we can notice in Fig. 15 (a), the grating ensuring the dispersion compensation in chirped. The chirp is not uniform along the grating and varies depending on the grating position. In Fig 15. (b), we illustrate the refractive index modulation shape, the apodization profile has the strength values at the central of grating and it cannot been approximated by a regular behavior.

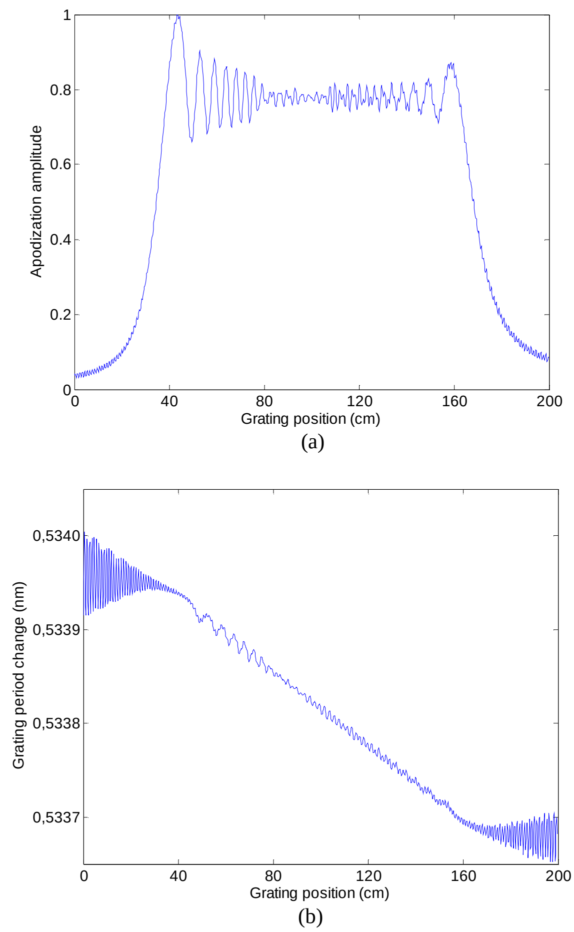


Figure 15. Grating period (a) and the apodization profile (b) of the synthesized FBG.

Fig. 16, represents the time delay of the FBG identified by the DLP process, with two other configuration to compensate chromatic dispersion of two fiber with L_F =100km and L_F=*50*km.

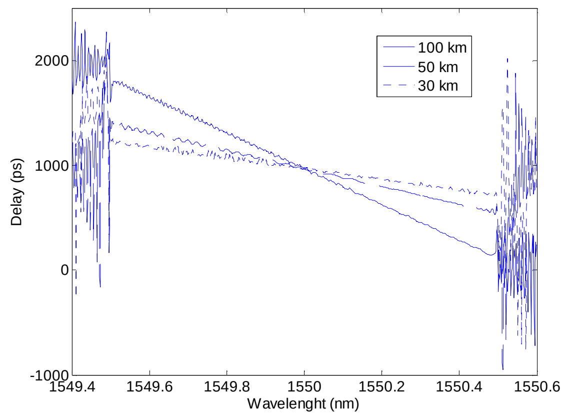


Figure 16. Time delay (ps) of the synthesis gratings at the working wavelength of 1550 nm to compensation chromatic dispersion of Fiber with three different length (30km, 50km and 100km).

In this case, we were able to compensate the chromatic dispersion at given wavelength of 1550. For a compensation within larger bandwidth, we can use superstructure FBG to achieve the desired compensation parameters.

V. CONCLUSION

This paper presents versatile numerical tools for synthesizing and designing fiber Bragg grating with potential application in optical communication systems. A simulation approach has been presented that includes potential applications in optical communication systems. We have adapted the DLP algorithm for synthesis of OCDMA encoder/decoder and dispersion compensation as potential application in high-speed optical communication system. We improved the GA method for designing OCDMA encoder/decoder, by introducing new inputs array, which lead to the synthesis of SPE-OCDMA. We presents also comparison study between the two main techniques of synthesis; layer peeling and genetic algorithm, in terms of accuracy and complexity depending on the application.

REFERENCES

[1] T. Erdogan, "Fiber Grating Spectra," IEEE Journal of Lightwave Technology, vol. 15, pp. 1277-1294, Aug. 1997.

[2] J. Salehi, "Code division multiple-access techniques in optical fiber networks-Part 1: Fundamental principles," IEEE Trans. Commun., vol. 37, pp. 824-833, Aug. 1989.

[3] D. Zaccarin and M. Kavehrad, "An optical CDMA system based on spectral encoding of LED," IEEE Photon. Technol. Lett., vol. 4, pp. 479-482, Apr. 1993.

[4] H. Fathallah, and L. A. Rusch, and S. LaRochelle, "Passive Optical Fast Frequency-Hop CDMA Communication System," Journal of Lightwave Technology, vol. 17, pp. 397-405, Mar. 1999.

[5] M. Mathlouthi, M. Menif, C. Lepers et H. Rezig, "DS-OCDMA Encoders/Decoders Synthesis Using Fiber Bragg Gratings", Photonics North 2007,Proceeding of SPIE, Vol. 6796, pp. 67963L-1-9, 4-7 June 2007.

[6] B. Dai and X. Wang "Novel FBG Decoder for Simultaneous Time Domain Coherent Optical Code Recognition and Chromatic Dispersion Compensation" IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 22, NO. 2, November 15, 2010.

[7] R. Feced, M. N. Zervas, and M. A. Muriel, "An efficient inverse scattering algorithm for the design of nonuniform fiber bragg gratings," IEEE Journal of Quantum Electronics, vol. 35, pp. 1105-1115, Aug. 1999.

[8] J. Skaar, and K. M. Risvik, "A genetic algorithm for the inverse problem in synthesis of fiber gratings," Journal of lightway technology, vol. 16, pp. 1928-1932, Oct. 1998.

[9] J. A. Dobrowolski and D. Lowe, "Optical thin film synthesis program based on the use of Fourier transforms," Appl. Opt., vol. 17, no. 19, pp. 3039-3050, Oct. 1978.

[10] B. G. Bovard, "Fourier transform technique applied to quarterwave optical coatings," Appl. Opt., vol. 27, no. 15, pp. 3062-3063, Aug. 1988.

[11] K. A. Winick and J. E. Roman, "Design of corrugated waveguide filters by Fourier-transform techniques," IEEE J. Quantum Electron., vol. 26, pp. 1918-1929, Nov. 1990.

[12] I. M. Gel'fand and B. M. Levitan, "On a determination of a differential equation from its spectral function," Amer. Math. Soc. Trasl., Ser. 2, vol. 1, pp. 253-304, 1955.

[13] A. M. Bruckstein, B. C. Levy, and T. Kailath, "Differential methods in inverse scattering," SIAM J. Appl. Math., vol. 45, no. 2, pp. 312-335. Apr. 1995.

[14] A. M. Bruckstein and T. Kailath, "Inverse scattering for discrete transmission-line models," SIAM Rev., vol. 29, no. 3, pp. 359-389, Sept. 1987.

[15] J. Skaar, L. Wang, and T. Erdugan, "On the synthesis of fiber bragg gratings by layer peeling," IEEE Journal of Quantum Electronics, vol. 37, pp. 165-173, Feb. 2001

[16] M. Mathlouthi, M. Menif, C. Lepers et H. Rezig, "Genetic Algorithm Synthesis of Spectral Phase OCDMA Decoders and Encoders", Photonics North 2008, Proceeding of SPIE, Vol. 7099, Montréal, paper PDS-3-6-1, 4-6 June 2008.

[17] I. Fsaifes, and C. Lepers, and A. Obaton, and P. Gallion, "DS-OCDMA Encoders/Decoders Performance Analysis using Optical Low Coherence Reflectometry," Journal of Lightwave Technology, vol. 24, pp. 3121-3128, Aug. 2006.

[18] L. Poladian, "Simple grating synthesis algorithm," Opt. Lett., vol. 25, pp. 787-789, 2000.

[19] M. A. Muriel, J. Azana, and A. Carballar, "Fiber grating synthesis by use of time-frequency representations," Opt. Lett., vol. 23, pp. 1526-1528, 1998.

[20] J.H. Holland, "Genetic algorithms and the optimal allocations of trials," SIAM Journal of Computing, (2), pp. 88-105, (1973).

[21] G. Tremblay, J-N Gillet, Y. Sheng, M. Bernier, and G. Paul-Hus, "Optimizing Fiber Bragg Gratings Using a Genetic Algorithm With Fabrication-Constraint Encoding," Journal of Lightwave Technology, vol. 23, pp. 4382-4385, Dec. 2005.

[22] G. Cormier and R. Boudreau "Real-coded genetic algorithm for Bragg grating parameter synthesis," Journal of optical Society of America, vol. 18, No.18 pp. 1771-1776, December 2001.

[23] M. Mathlouthi, M. Menif, C. Lepers and Houria Rezig, "Comparison of Synthesis Techniques for SPE-OCDMA Encoders/Decoders Based on FBGs", Proceeding IEEEICTON-MW2008, Marrakech, Morocco, 11-13 Dec. 2008, pp. 1-6, 2008.