Synthesis of Broadband Transmission Filters By Layer-peeling and a Genetic Algorithm

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***Abstract*— We present a method to reconstruct optical transmission filters from specific complex spectrum profiles. A discrete inverse scattering method, known as layer-peeling, is used recursively to reconstruct a long-period fibre grating structure from a specified realisable complex spectrum by a direct solution of the coupled-mode equations or transfer matrices, while simultaneously determining the physical properties of the layered structure. The relative short computation time when compared to genetic algorithms, and low algorithm complexity are the main advantages of the layer-peeling method. We demonstrate this layer-peeling method by applying it to the design of high performance broadband transmission filters, for application in dense wavelength division multiplexing (DWDM) systems. The theoretical results obtained from this layer-peeling method are compared to results obtained from a genetic algorithm, and a conclusion is drawn about the overall performance of the layer-peeling algorithm.**

***Index Terms*— Transmission filters, complex spectrum, layer-peeling method, genetic algorithm, broadband, dense wavelength division multiplexing (DWDM).**

I. INTRODUCTION

THE SYNTHESIS of optical filters, such as fibre gratings, have attracted many researchers in the field of fibre optics to find ways of obtaining a grating structure from a specified, complex spectrum. At present, high-speed optical fibre communication devices rely on advanced optical filters to perform various tasks such as compensation of link dispersion [1] or gain flattening of erbium-doped fibre amplifiers [2]. It is important when designing filters, to strictly monitor the complexity of the index modulation of the grating, such that it can be practically realised in the fibre core during the grating manufacturing process. It is recommended when designing advanced fibre gratings, to permit accurate control of both the apodization profile and the local grating pitch along the grating structure [3].

Optical filter design consists of two parts, namely filter synthesis and filter analysis [4]. In the analysis of optical filters, the reflection/transmission spectra, time delay, and dispersion properties are calculated, given a known physical optical filter structure. However, the filter synthesis approach entails the derivation of the structure and physical properties of an optical filter from a desired spectrum [4], [5]. Figure 1 illustrates the relationship between filter synthesis and filter analysis. In this paper we are considering two synthesis methods. The first synthesis method is known as the inverse scattering technique that uses simple causality arguments to reconstruct the coupling coefficient and filter spectrum from a desired target spectrum [5]. The second synthesis method is the genetic algorithm, which is a probabilistic search algorithm based on natural selection, commonly used to seek results in large search spaces [4].

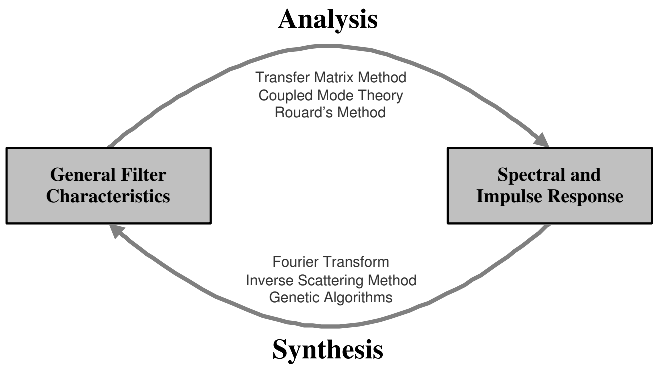

Fig. 1. Relationship between optical filter synthesis and analysis [4].

The grating synthesis problem is by no means trivial, especially compared to the well-known direct problem of computing the spectrum from a specific grating structure. At present, several inverse scattering algorithms exist, which are used in various fields of study [5]–[7]. Poladian *et al.* [8] indicated that the synthesis problem actually is as simple as the forward problem.

There exist two variations of the inverse scattering layer-peeling algorithm. These are the discrete layer-peeling method (DLP), and the continuous layer-peeling method (CLP) [7]. While the implementation of the DLP and CLP method differs, the principle behind these methods is the same. The DLP is often more stable and significantly faster than the CLP method, but in both methods convergence problems (due to the accumulation of numerical errors along the grating structure) are found when strong fibre gratings are reconstructed [9]. It has been shown that reflection and transmission filter structures can be reconstructed efficiently from a desired complex spectrum using the layer-peeling method [5], [10].

When designing complex optical filters it is often desirable to consider a weighting mechanism, which makes it easier to balance the different requirements. An example may be to weight linear phase more than induced index change, because dispersion may be a more critical factor. In retrospect one can choose which parameters are more important than others during the synthesis problem, making this approach more flexible than the layer-peeling approach. Optimization methods such as genetic algorithms (GAs) are ideally suited for this task. Genetic algorithms have the capability of obtaining an index modulation profile that can be more practically implemented in the fibre core, by specifying restrictions to specific parameters in the design [2]. Genetic algorithms have been applied to design fibre Bragg gratings (FBGs) [11] and long-period fibre gratings (LPGs) [2]. However, the computation time it takes to obtain a suitable solution to the synthesis problem using a GA is very long. The genetic algorithm approach is slow, due to the large number of individuals and generations required, but it produces results which can be practically implemented.

The remainder of the paper is organised as follows. In Section II the inverse scattering layer-peeling method is briefly discussed, and theoretical design results are produced for optical transmission filters. Section III discusses the basic concepts behind a genetic algorithm and provides results obtained for the same type of optical filter. Concluding remarks are given in Section VI about the two different algorithms used to design high performance transmission filters.

II. Transmission Filter Synthesis by Layer-peeling Algorithm

In this section the inverse scattering method proposed by Feced *et al.* [10] is used to obtain the reconstructed LPG spectra from a target core mode spectrum. The refractive-index modulation of a fibre grating along the optical fibre propagation axis can be written as [12]:

$$n(z) = n_a + \overline{\delta n}_{core}\left\{\upsilon \cos\left(\frac{2\pi}{\Lambda}z + \phi(z)\right)\right\} \tag{1}$$

where Λ is the grating period, n_a is the average effective refractive-index, $\phi(z)$ denotes the local phase variation and grating chirp, υ is the fringe visibility, and $\overline{\delta n}_{core}$ is the induced index change spatially averaged over the fibre grating period. Based on the coupled-mode theory, the coupling between two co-directional propagating modes is described by the well-known coupled-mode equations [12]:

$$\begin{aligned} \frac{dU(z,\delta)}{dz} &= i\delta U(z,\delta) + iq(z)W(z,\delta) \\ \frac{dW(z,\delta)}{dz} &= iq^*(z)U(z,\delta) - i\delta W(z,\delta) \end{aligned} \tag{2}$$

where $U(z,\delta)$ and $W(z,\delta)$ are the slowly varying amplitudes of the co-directional propagating modes, and $q(z)$ is the coupling coefficient. The detuning parameter δ for LPG structures is defined as [12]:

$$\delta \equiv \frac{1}{2}\Big(\beta_{core} - \beta^{\mu}_{clad}\Big) - \frac{\pi}{\Lambda} \tag{3}$$

where β_{core} is the propagation constant of the core mode, and β^{μ}_{clad} is the propagation constant of the μ^{th} cladding mode.

The use of inverse scattering methods to reconstruct an LPG is by no means an easy task to perform, since a reflection grating is an infinite-impulse-response (IIR) filter, and a transmission filter (i.e. long-period grating) is a finite-impulse-response (FIR) filter [13]. These types of optical filters have distinct restrictions on the relationships between the phase and amplitude responses for each filter. For transmission filters the entire grating structure is necessary to determine the points in the impulse response, and special care should be taken in the formulation of the inverse scattering algorithm to reconstruct these types of filters [14], [15]. The discretised-coupling model of an LPG is illustrated in figure 2.

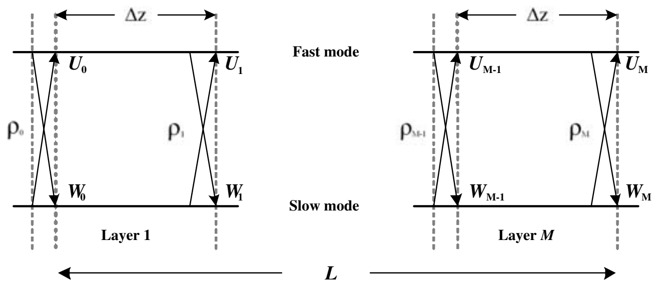

Fig. 2. The discrete model of an LPG structure [15].

The grating structure is divided into M layers separated by a distance Δz, and the main aim is to obtain the required strength of the instantaneous scattering points ρ_M, given a valid pair of transmission $U_M(z,\delta)$ and cross-coupling $W_M(z,\delta)$ spectra [15]. From equation 4, U_j and W_j are the amplitudes of the fields traversing through a section j of length Δz, where the coupling coefficient $q(j\Delta z)$ is unique for each section j. The matrix G describes the propagation through each section j and is given by [14], [15]:

$$\begin{bmatrix} U_M \\ W_M \end{bmatrix} = (G_M G_{M-1} \cdot \ldots \cdot G_j \cdot \ldots \cdot G_1) \begin{bmatrix} U_0 \\ W_0 \end{bmatrix} \tag{4}$$

where

$$G_j = \begin{bmatrix} S_{lpg1} + i\frac{\delta}{\gamma_L}S_{lpg2} & i\frac{q}{\gamma_L}S_{lpg2} \\ i\frac{q^*}{\gamma_L}S_{lpg2} & S_{lpg1} - i\frac{\delta}{\gamma_L}S_{lpg2}) \end{bmatrix} \tag{5}$$

and $\gamma_L \equiv \sqrt{|q|^2 + \delta^2}$. The elements in the above matrix equations are defined as: $S_{lpg1} = \cos(\gamma_L \Delta z)$, and $S_{lpg2} = \sin(\gamma_L \Delta z)$. The piecewise uniform coupling model [12] can be further approximated by separating the distributed coupling that takes place in a grating structure, into a stack of discrete instantaneous scattering points [10]. The matrix G_ρ describes the coupling in the j^{th} layer of an LPG structure, and the other, G_Δ, describes the propagation between the instantaneous scattering points [15]:

$$G_\rho = (1 + \mid \rho \mid^2)^{-1/2} \begin{bmatrix} 1 & \rho \\ -\rho^* & 1 \end{bmatrix} \quad (6)$$

$$G_\Delta = \begin{bmatrix} \exp(i\delta\Delta z) & 0 \\ 0 & \exp(-i\delta\Delta z) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} U_j(\delta) \\ W_j(\delta) \end{bmatrix} = G_\Delta G_\rho \begin{bmatrix} U_{j-1}(\delta) \\ W_{j-1}(\delta) \end{bmatrix} \quad (8)$$

where $1 \leq j \leq M$, and the discrete coupling coefficient is obtained from the coefficients ρ_j using the relation [15]:

$$q(j\Delta z) = -\frac{1}{\Delta z} \frac{\rho_j^*}{\mid \rho_j \mid} \arctan(\mid \rho_j \mid). \quad (9)$$

If we reformulate the discretised-coupling model into the space-time domain, the inverse-scattering method will be the most efficient [10]. Let us assume that a normalised spectrum is incident to the fast mode U and nothing to the slow mode W. The time delay is defined such that the light propagates in the medium without delay in the fast mode. Since the time domain field vectors at layer j is related to the spectral fields by a discrete-time inverse Fourier transform, they are discrete and have contributions from all possible paths as illustrated in figure 2 [15]. From figure 2 the responses at any layer consist of at most $M+1$ pulses, since a unit impulse is incident to the fast mode and no light to the slow mode. The time-domain field coefficients are defined as follows [15]:

$$\begin{aligned} U_j(\delta) &= \textstyle\sum_{\tau=0}^{M} u_j(\tau)\exp(i2\Delta z\delta\tau) \\ W_j(\delta) &= \textstyle\sum_{\tau=0}^{M} w_j(\tau)\exp(i2\Delta z\delta\tau) \end{aligned} \quad (10)$$

where $\tau = 0, 1, ..., M$, the spectral fields $U_j(\delta)$ and $W_j(\delta)$ are periodic with a period $\pi/\Delta z$. From equation 10 it takes the signal the normalised time $2\Delta z$ to propagate through one layer in the slow mode. The transfer matrix model defined in equation 8, can be easily transformed to the time-domain, where G_Δ operates by delaying the slow mode by one time unit with respect to the fast mode [15]:

$$\begin{bmatrix} u_j(\tau) \\ w_j(\tau) \end{bmatrix} = G_\rho \begin{bmatrix} u_{j-1}(\tau) \\ w_{j-1}(\tau-1) \end{bmatrix}, \quad 1 \leq j \leq M. \quad (11)$$

At the end of the LPG structure (i.e. layer M), the time-domain response is given as follows [14], [15]:

$$\begin{aligned} u_M(\tau) &= [u_M(0) \;\; u_M(1) \;\; ... \;\; u_M(M)] \\ w_M(\tau) &= [w_M(0) \;\; w_M(1) \;\; ... \;\; w_M(M)] \end{aligned} \quad (12)$$

where $u_M(0)$ and $w_M(0)$ denote the two shortest optical paths through the LPG structure from causality requirements. The discrete coupling ratio in the grating structure is then simply expressed as $\rho_M = w_M(0)/u_M(0)$. Since the value of ρ_M is known at the final layer, we can now remove this layer and obtain the impulse responses of layer $M-1$ as follows [15]:

$$u_{M-1}(\tau) = \frac{u_M(\tau) + \rho_M^* w_M(\tau)}{\sqrt{\mid \rho_M \mid^2 + 1}} \quad (13)$$

$$w_{M-1}(\tau - 1) = \frac{w_M(\tau) - \rho_M u_M(\tau)}{\sqrt{\mid \rho_M \mid^2 + 1}}. \quad (14)$$

Equations 13 and 14 can now be used to obtain the discrete coupling ratio ρ_{M-1}, and this procedure is repeated until all the layers have been reconstructed [15]. However, Erdogan *et al.* [14] have provided simplified expressions for the field amplitudes at the end of the M^{th} layer, after considering that light starts propagating in the core and travels until the end of the M^{th}-layered LPG structure as illustrated in figure 3.

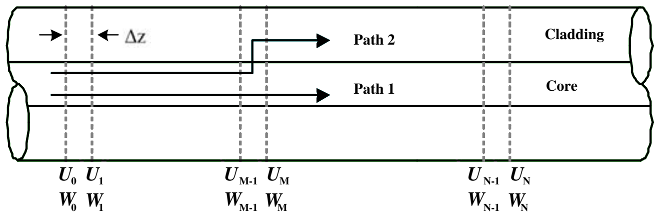

Fig. 3. Illustration of an long-period grating structure indicating the two optical paths associated with the m^{th} layer [14].

According to Erdogan *et al.* the impulse response has a contribution from only path 1 in figure 3 during core mode transmission at time $\tau_1 = n_{core}\Delta z M/c$, and for cladding mode transmission the impulse response has a contribution from only path 2 at time $\tau_2 = [n_{core}\Delta z M/c - (n_{core} - n_{clad})\Delta z/2c]$. The impulse responses in the time domain for core mode and cladding mode transmission are given as $h_M^{core,clad}(\tau) = \int \tau_M^{core,clad} \exp(-i\omega\tau)d\omega/2\pi$. The transmission functions t_M^{core} and t_M^{clad} are defined as follows [14]:

$$\begin{aligned} t_M^{core} &= U_M(\delta)e^{[-(iM\Delta z\delta)+(iM\Delta z\beta_{core})]} \\ t_M^{clad} &= W_M(\delta)e^{[+(iM\Delta z\delta)+(iM\Delta z\beta_{clad}^{\mu})]}. \end{aligned} \quad (15)$$

Given a realisable complex spectrum $t(\delta)$ in the interval $-\delta_w/2 \leq \delta \leq \delta_w/2$, the aim is to find the coefficients ρ_j for $j = 1, 2, ..., M$ [15]. The bandwidth $\delta_w = \pi/\Delta z$ is usually specified, which normally dictates the spatial resolution. The layer-peeling algorithm is based on the fact that the first point of the impulse response must be independent of the ρ_j's for $j \geq 2$ due to causality, thus $\rho_1 = h(1)$. Since ρ_1 is known, we can simply propagate the fields using the transfer matrices. The discrete layer-peeling algorithm may now be summarised as follows:

- (1) Start with a physically realisable complex spectrum $t(\delta)$. One should specify a desired cross-coupling spectrum $W(\delta)$, and design an M^{th} order FIR filter using,

- e.g., windowing. After designing the FIR filter, one should then obtain the polynomial $U(z)$ by a root-finding procedure, or using the discrete Hilbert transform [15], where $U(z)U_*(z) + W(z)W_*(z) = 1$ (the asterisk in the subscript indicate the para-Hermitian conjugate). The z-transform of the impulse responses $u(\tau)$ and $w(\tau)$, produces the M^{th} order polynomials $U(z)$ and $W(z)$.
- (2) Calculate the coefficient ρ_j.
- (3) Propagate the fields using the transfer matrices from equations 13 and 14.
- (4) Repeat step (2) until the entire filter structure is reconstructed.

A count of the number of operations for this algorithm shows that the running time is in the order of $O(M^2)$ when compared to the conventional approach of computing the direct problem. We now consider an example where the target cross-coupling spectrum in the cladding has a flat-top, nearly rectangular passband described by a "Super-Gaussian" function [7]:

$$t(\delta) = \sqrt{R} \times \exp\left(\frac{\delta}{\delta_{pb}}\right)^{20} \qquad (16)$$

where the maximum transmission in the passband is $R = 0.99$, and the desired passband width δ_{pb} at full-width half-maximum (FWHM) is 11 nm. The designed wavelength is $\lambda_R = 1550$ nm, and the effective refractive index difference between the two interacting modes is $\Delta n_{eff} = 3.4 \times 10^{-3}$. The grating period equals $\Lambda = 456$ μm. The length of the grating is $L_{lpg} = 30$ mm, and the number of layers used to reconstruct the transmission spectrum were $N = 202$. The simulation results of the transmission filter reconstructed using the discrete layer-peeling method are illustrated in figures 4 and 5.

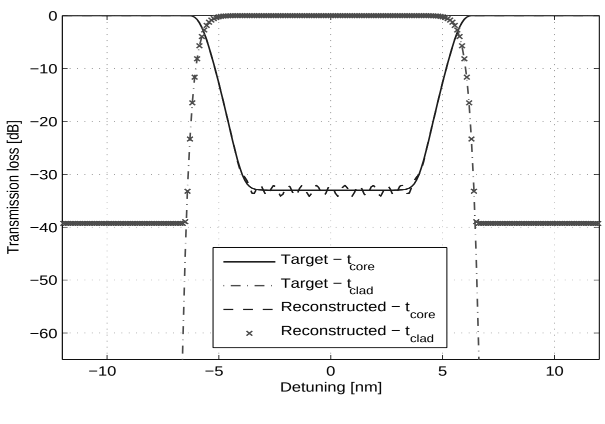

Fig. 4. Target/Reconstructed LPG transmission spectrum for the core mode and cross-coupling spectrum for the cladding mode in logarithmic scale.

From figure 4 the core mode transmittance was kept to -34 dB (with a ~ 2 dB ripple in the passband of the core mode spectrum), and the cladding mode transmittance did not exceed -39 dB, indicating that this is a very strong transmission filter. The coupling coefficient illustrated in figure 5 did not exceed $11.67\ cm^{-1}$, the maximum index change obtained was 0.58×10^{-3}, and the grating chirp was 3.66 nm/cm. It was found that the LPG structure exhibited a sinc-like envelope, and has uniform periods, where there exists a π phase shift at each minimum point of the index modulation profile. Zhang *et al.* illustrated similar effects on the modulation index when reconstructing LPGs using the layer-peeling method [16]. It took only 786 milliseconds to reconstruct the LPG on a 2.66 GHz Pentium 4 computer using MATLAB 7.

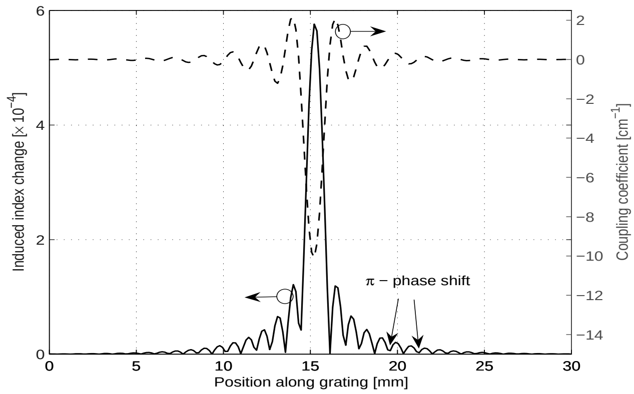

Fig. 5. Reconstructed LPG coupling coefficient (1/cm) and index modulation profile simulated using the layer-peeling method.

However, to implement the results presented in a manufacturing process, these results must first be adjusted such that it is more practically suited for the manufacturing of an LPG. Figures 6→8 illustrate theoretical results obtained when the index modulation profile was adjusted in such a way as to allow the filter structure to be practically realisable. From figure 8 the dispersion result is small (exhibiting a small ripple in the passband) when the LPG is reconstructed, but increases when the filter structure results are adjusted for practical implementation.

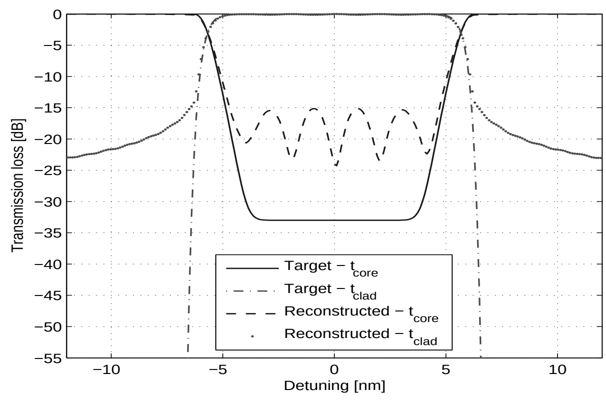

Fig. 6. Target/Reconstructed LPG transmission spectrum for the core mode and cross-coupling spectrum for the cladding mode in logarithmic scale considering practical implementation issues.

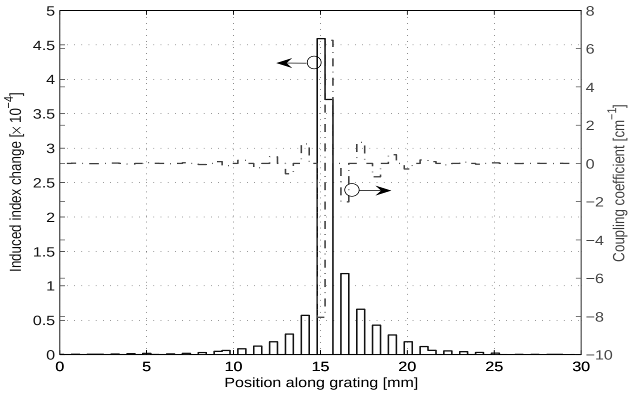

Fig. 7. Reconstructed LPG coupling coefficient (1/cm) and index modulation profile simulated using the layer-peeling method considering practical implementation issues.

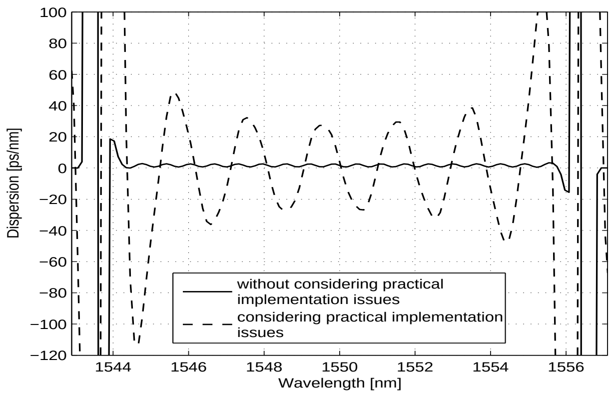

Fig. 8. Filter dispersion obtained using the layer-peeling method after practical implementation issues were considered.

III. Transmission Filter Synthesis by Genetic Algorithm

Genetic algorithms are probabilistic parallel search algorithms, which are based on natural selection [4], following the same principle as the evolutional process of nature. In the following example an attempt is made to reconstruct a transmission filter using a genetic algorithm. The constraints placed on the design are as follows: A fixed value was chosen for the length, bandwidth and power of the transmission filter. The genetic algorithm was then used to obtain the required refractive index profile for the filter structure, from a pre-specified transmission spectrum. The starting population of the genetic algorithm was generated randomly, consisting of M chromosomes, each consisting of N codons, which represent the N random numbers generated between the upper and lower bounds of the coupling coefficient for the specific design. After the target spectrum is specified and the number of populations and generations are set, the genetic algorithm is executed until the target spectrum is reached.

The genetic algorithm optimization toolbox (GAOT) developed by Joines *et al.* [17] was used to reconstruct the long-period grating structure. The target transmission was set to 0.9, operating at a center wavelength of 1550 nm, with a 52 nm bandwidth at FWHM. The spectrum was designed to exhibit a "Super-Gaussian"-profile, the grating length was chosen to be 40 mm, and the grating period was 465 μm. The lower and upper bounds of the coupling coefficient was set to 0 and 184 cm^{-1}, respectively. The induced index change of the designed filter exhibits a positive hyperbolic tangent profile, and the filter was designed to exhibit a grating chirp of 13 nm/cm. Figure 9 illustrates the target and reconstructed transmission spectrum of an non-uniform LPG, as well as theoretical results obtained when the filter structure is adjusted such that it can be practically realised.

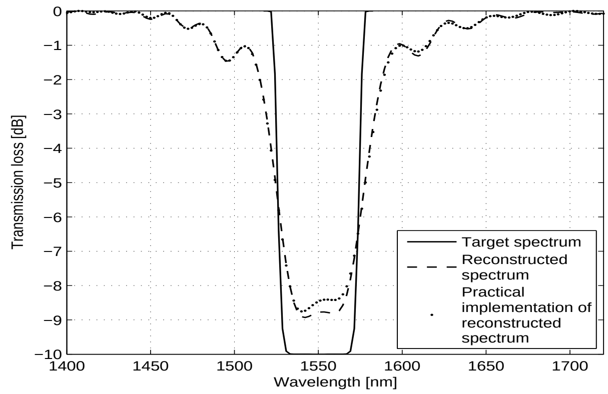

Fig. 9. Target/Reconstructed transmission spectrum of a non-uniform LPG simulated using a genetic algorithm.

The target spectrum differs from the reconstructed spectrum, in the sense that the reconstructed spectrum bandwidth does not match the target set. However, the grating chirp influences the LPG structure dramatically, as well as the implementation of the apodization profile. The hyperbolic tangent apodization profile [18] was chosen, since it provided the best results in maintaining a broad bandwidth, a near flat top passband, a maximum reduction in the time delay ripple, and a minimal reduction in transmission loss. Other apodization profiles failed in maintaining a broad bandwidth, and a near flat top spectrum. However, the small sidelobes in the reconstructed spectrum are a problem, but an efficient LPG structure has been reconstructed, exhibiting a high transmission loss. The initial individuals in the population was set to 150, and the genetic algorithm searched for optimal solutions in only 200 generations. From figure 9 the reconstructed LPG results obtained correspond in some ways to the target set, where a maximum transmission loss of -8.93 dB was obtained, with a passband bandwidth of 53 nm, operating at a center wavelength of 1550 nm. The passband ripple was ~ 0.16 dB, indicating that the reconstructed spectrum did not have a flat top.

Figure 10 illustrates the index modulation profile of the reconstructed transmission filter, where a maximum index change of 9.09×10^{-3} was obtained. The genetic algorithm searched for results in a wide range of coupling coefficient values, and the results obtained look very promising for future simulations. The genetic algorithm executed for approximately $2\frac{1}{2}$ hours to obtain the results, indicating that this algorithm takes a long time to obtain a desired result.

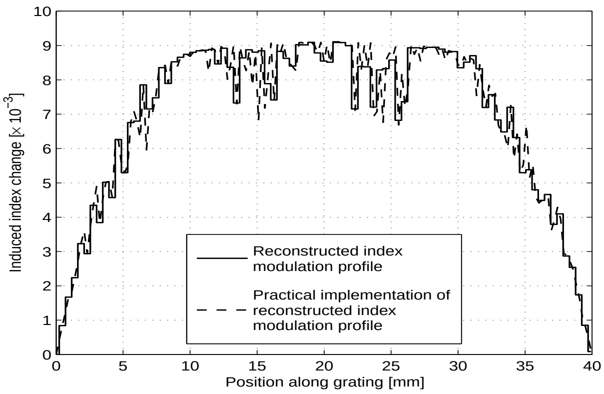

Fig. 10. Reconstructed index modulation profile of a non-uniform LPG using a genetic algorithm.

IV. Conclusion

Methods to reconstruct transmission filters from a realisable complex spectrum, for applications in DWDM network systems have been discussed. The reconstruction of transmission filter structures have been demonstrated by means of implementing two synthesis algorithms, namely the layer-peeling algorithm, and the genetic algorithm. When these two algorithms are compared, there are a few aspects that separates these two methods, especially when one looks at the results obtained in this paper. The layer-peeling algorithm succeeded in reconstructing a broadband transmission filter very quickly and accurately, but the modulation index results are somewhat complex to implement in a manufacturing process. However, the genetic algorithm technique had a problem to reconstruct transmission filters, because of the complex nature of the LPG structure. This algorithm was very time consuming in producing results. The index modulation profile results obtained from the GA, looked in the end more practical to implement in a manufacturing process, when it is compared to results obtained from the layer-peeling method. A trade-off between computation time and implementation complexity for the synthesis algorithms should be made in order to obtain a solution that will be acceptable for the individual.

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