EngOpt 2008 - International Conference on Engineering Optimization
Rio de Janeiro, Brazil, 01 - 05 June 2008.

Design of Code Division Multiple Access Filters Using Global Optimization Techniques

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Abstract: A semi-deterministic global optimization algorithm is briefly presented and applied to the design of code division multiple access filters based on sampled fiber Bragg gratings. We focus on the developing of a particular design corresponding to a filter that generates a code of length 8.

Keywords: global optimization; inverse problems; descent algorithms; optical fibers; Code Division Multiple Access.

1 Introduction

The use of optical fiber which offers a large bandwidth (about five TeraHertz per telecommunication window) in the telecommunication sector has known an important development in the last decade [21]. However, they can be fully used only if the techniques of multiple access, allowing various persons (called 'users') to send a message in the fiber at the same time, are sufficiently effective. There exist three main schemes of access in order to share the large bandwidth of an optical communication link: Time division multiple access (TDMA) [5] which authorizes to consider a great number of users but requires fast synchronization, wavelength-division multiplexing (WDM) [1] which sometimes requires precise adjustments, and code division multiple access (**CDMA**) [19] which primarily allows a great flexibility in multiple accesses. This last technique presents various advantages such as resistance to signal perturbations, secured communications and low power consum [22].

In the basic technique of CDMA, the bits '1' or '0' of a binary message, send by an user, are replaced at the level of the transmitter by codes attributed to this user. The code for the bit '1' of a particular user 'A' is denoted by $c_1^A \in \{0,1\}^{N_{\text{code}}}$ and its complement denoted by $c_0^A = -(c_1^A - 1)$ is used for '0', where $N_{\text{code}} \in \mathbb{N}$ is the code length. Zaccarin and Kavehrad [15] and Lam [16] suggested to use spectra, compound by a set of wavelengths $(\lambda_i)_{i=0}^{N_{\text{code}}}$, in order to represent those codes (i.e. the reflectivity of $\lambda_i = c(i)$, for $i = 1, ..., N_{\text{code}}$, where c is the considered code). One way to generate such a spectrum is to consider sampled fiber Bragg grating (**SFBG**).

SFBGs represent an attractive device for applications such as multichannel filtering, multichannel optical add/drop multiplexing, multichannel dispersion compensation and multi-wavelength laser sources. They are based on a periodic perturbation (called 'sampling pattern') of the effective refractive index of an optical guide, obtained by exposing it to UV radiations [4], in order to reflect predetermined wavelengths and to let other wavelengths pass [2, 23]. They can be easily hybridized with other optical devices [6] as the 'optical isolator' presented later in this paper. Currently, there is an important demand for optimization methods for the design of sampling patterns giving a desired reflectivity spectrum [20]. However, the optimization method needs to perform global optimization as it has been observed that the considered functionals have multiple minima [21].

In this paper, we focus on the application of a semi-deterministic global optimization algorithm for the design of a particular CDMA filter.

Section 2 describes our optimization method and a particular implementation. In Section 3, we introduce the considered CDMA filter and its mathematical modeling. Finally in Section 4, we present the inverse problem associated to the design of SBFGs and study a particular numerical problem.

2 Semi-deterministic global optimization method

2.1 General description of the method

We introduce the following minimization problem:

$$\min_{x\in\Omega} h_0(x) \tag{1}$$

where $h_0 : \Omega \to \mathbb{R}$ is the cost function and x is the optimization parameter belonging to an admissible space $\Omega \subset \mathbb{R}^N$, with $N \in \mathbb{N}$. We assume $h_0 \in C^0(\Omega, \mathbb{R})$ is a coercive function (i.e. $\lim_{\|x\|\to+\infty} h_0(x) = +\infty$).

We consider an optimization algorithm $A_0 : V \to \Omega$, called 'core optimization algorithm', to solve (1). Here V is the space where we can choose the initial condition for A_0 (an example is given in Section 2.2). The optimization parameters of A_0 (such as the stopping criteria parameters, etc...) are chosen by the user at the beginning.

We assume the existence of a suitable initial condition $v \in V$ such that the output returned by $A_0(v)$ approaches a solution of (1). In this case, solving numerically (1) with the considered core optimization algorithm can be formulated as follows:

$$\left\{\begin{array}{l}\text{Find } v \in V \text{ such that}\\ A_0(v) \in \text{argmin}_{x\in\Omega} h_0(x).\end{array}\right. \tag{2}$$

In order to solve (2), we propose to use a multi-layer semi-deterministic algorithm based on line search methods (see, for instance, [18]) called, for the sake of simplicity, 'Semi-Deterministic Algorithm' (**SDA**).

We introduce $h_1 : V \to \mathbb{R}$ by

$$h_1(v) = h_0(A_0(v)). \tag{3}$$

Thus problem (2) can be rewritten as:

$$\left\{\begin{array}{l}\text{Find } v \in V \text{ such that}\\ v \in \text{argmin}_{w\in V} h_1(w).\end{array}\right. \tag{4}$$

An example of the geometrical representation of $h_1(.)$ in one dimension is shown in Figure 1 for a situation where the core optimization algorithm is the steepest descent algorithm [18] applied with a large number of iterations. We see that $h_1(.)$ is discontinuous with plateaus. Indeed, the same point is reached by the algorithm starting from any of the points of the same attraction basin. Furthermore, $h_1(.)$ is discontinuous where the functional reaches a local maximum. One way to minimize such a kind of function, in the one dimensional case, is to consider line search optimization methods (such as secant method or dichotomy [18]).

Thus, in order to solve (4), we introduce the algorithm $A_1 : V \to V$ that, for each $v_1 \in V$, returns $A_1(v_1)$ given by

Step 1- Choose v_2 randomly in V.

Step 2- Find $v \in \text{argmin}_{w\in\mathcal{O}(v_1,v_2)} h_1(w)$, where $\mathcal{O}(v_1, v_2) = \{v_1 + t(v_2 - v_1), t \in \mathbb{R}\} \cap V$, using a line search method.

Step 3- Return v.

The line search minimization algorithm in A_1 and its corresponding parameters are defined by the user.

In fact, we are interested to perform a multi-directional search of the solution of (2). To do so, we add a layer external to the algorithm A_1 by considering the following methodology:

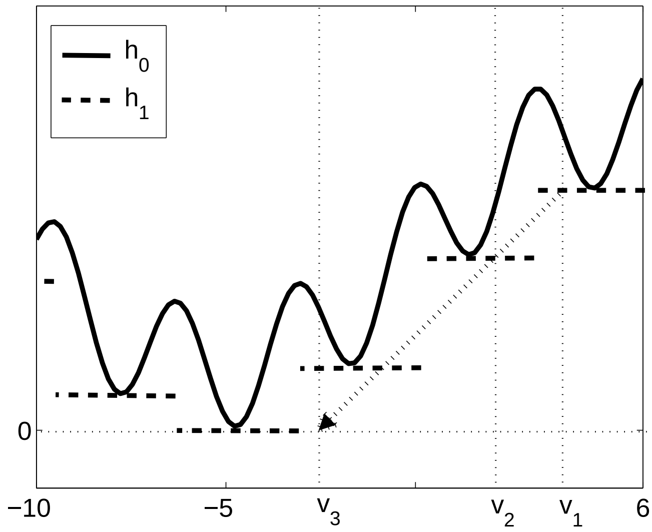

Figure 1: (—) $h_0(x) = \frac{1}{2}\cos(2x) + \sin(\frac{1}{3}x) + 1.57$ for $x \in \Omega = V = [-10, 6]$. **(- -)** Geometrical representation of h_1 when the steepest descent method is used as core optimization algorithm with a large number of iterations. **(...)** Geometrical representation of one execution of the algorithm $A_1(v_1)$, written in Section 2.2, when v_1 is given and $t_{l_1} = 1$. v_2 is generated randomly $\in [-10, 6]$ during the first Step of the algorithm. v_3 is built by the secant method performed during the Step 2.2. During the Step 3, since $h_1(v_3)$ is lower than $h_1(v_1)$ and $h_1(v_2)$, v_3 is considered as the best initial condition and it is returned as the output.

We define $h_2 : V \to \mathbb{R}$ by

$$h_2(v) = h_1(A_1(v)) \tag{5}$$

Then we consider the problem:

$$\begin{cases} \text{Find } v \in V \text{ such that} \\ v \in \text{argmin}_{w \in V} h_2(w). \end{cases} \tag{6}$$

To solve (6) we use the two-layer algorithm $A_2 : V \to V$ that, for each $v_1 \in V$, returns $A_2(v_1)$ given by

Step 1- Choose v_2 randomly in V.

Step 2- Find $v \in \text{argmin}_{w \in \mathcal{O}(v_1, v_2)} h_2(w)$ using a line search method.

Step 3- Return v.

As previously, the line search minimization algorithm in A_2 and its corresponding parameters are defined by the user. Due to the fact that the line search direction $\mathcal{O}(v_1, v_2)$ in A_1 is constructed randomly, the algorithm A_2 perform a multi-directional search of the solution of (2).

This construction can be pursued recursively by defining for $i = 3, 4, ...$

$$h_i(v) = h_{i-1}(A_{i-1}(v)) \tag{7}$$

and considering the problem:

$$\begin{cases} \text{Find } v \in V \text{ such that} \\ v \in \text{argmin}_{w \in V} h_i(w). \end{cases} \tag{8}$$

Problem (8) is solved using the i-layer algorithm $A_i : V \to V$ that, for each $v_1 \in V$, returns $A_i(v_1)$ given by

Step 1- Choose v_2 randomly in V.

Step 2- Find $v \in \text{argmin}_{w \in \mathcal{O}(v_1,v_2)} h_i(w)$ using a line search method.

Step 3- Return v.

As before, the line search method used in Step 2 and its corresponding parameters are defined by the user.

In practice we run A_i with suitable stopping criteria and with $v_1 \in V$ arbitrary (or $v_1 \in V$ a good initial guess, if available).

The choice of the random technique used to generate v_2 during Step 1 of A_i is important and could depend on the shape of h_0. For instance, if we know that h_0 has several local minima in Ω with small attraction basins, it seems appropriate to generate v_2 in a small neighborhood of v_1.

The line search minimization algorithm used during Step 2 of A_i could depend on the properties of h_0.

A complete description of this method and various implementation schemes can be found in the following literature [9, 12]. In Section 2.2, we present a particular implementation of the SDA, considering a descent algorithm as core optimization algorithms, in the case where h_0 is a non negative function with zero as the minimum value. This often occurs in industrial problems [11], especially when considering inverse problems [10] as the one introduced in Section 4.1.

2.2 SDA implementation with descent core optimization algorithms

We consider core optimization algorithms A_0 that come from the discretization of the following initial value problem [17, 18]:

$$\begin{cases} M(x(t),t)x_t(t) = -d(x(t)), \quad t \geq 0, \\ x(0) = x_0, \end{cases} \tag{9}$$

where t is a fictitious time, $x_t = \frac{\mathrm{d}x}{\mathrm{d}t}$, $M : \Omega \times \mathbb{R} \to M_{N\times N}$ (where $M_{N\times N}$ denotes the set of matrix $N \times N$) and $d : \Omega \to \mathbb{R}^N$ is a function giving a descent direction. For example, assuming $h_0 \in C^1(\Omega, \mathbb{R})$, if $d = \nabla h_0$ and $M(x,t) = Id$ (the identity operator) for all $(x,t) \in \Omega \times \mathbb{R}$ we recover the steepest descent method.

According to previous notations, we use $V = \Omega$ and denote by $A_0(x_0) := A_0(x_0; t_0, \epsilon)$ the solution returned by the core optimization algorithm starting from the initial point $x_0 \in \Omega$ after $t_0 \in \mathbb{N}$ iterations and considering a stopping criterion defined by $\epsilon \in \mathbb{R}$.

We consider a particular implementation of the algorithms A_i, $i = 1, 2, ...,$ introduced previously. For $i = 1, 2, ...,$ $A_i(v_1)$ is applied with a secant method (a low-cost method well adapted to find the zeros of a function [18]) in order to perform the line search. It reads:

Step 1- Choose $v_2 \in \Omega$ randomly.

Step 2- For l from 1 to $t_{l_i} \in \mathbb{N}$ (large enough) execute:

Step 2.1- If $h_i(v_l) = h_i(v_{l+1})$ go to **Step 3**

Step 2.2- Set $v_{l+2} = \text{proj}_\Omega(v_{l+1} - h_i(v_{l+1}) \frac{v_{l+1} - v_l}{h_i(v_{l+1}) - h_i(v_l)})$
where $\text{proj}_\Omega : \mathbb{R} \to \Omega$ is a projection algorithm over Ω defined by the user.

Step 3- Return the output: $\text{argmin}\{h_i(v_m), m = 1, ..., t_{l_i}\}$

A geometrical representation of one execution of the algorithm A_1 in a one dimension example is shown in Figure 1.

3 CDMA filter

3.1 Considered CDMA device

We propose here to design a part of a transmitter based on CDMA codes. More precisely, we will design the code separator of a particular user 'A' depicted in Figure 2. The objective of this code separator is to separate the spectrum corresponding to the bits '1' and '0' of 'A'. It is formed by:

Part 1 An Optical Isolator: When an optical signal enters in the forward sense the signal is redirected to a SFBG. When a signal enters in the backward sense it is redirected to a classical fiber.

Part 2 A SFBG which reflects the spectrum corresponding to the bit '1' of 'A'.

Part 3 A classical optical fiber.

Here, we focus on the design of the the SFBG used in the Part 2. To do so, we first present a mathematical model used to compute the spectral response of SFBGs.

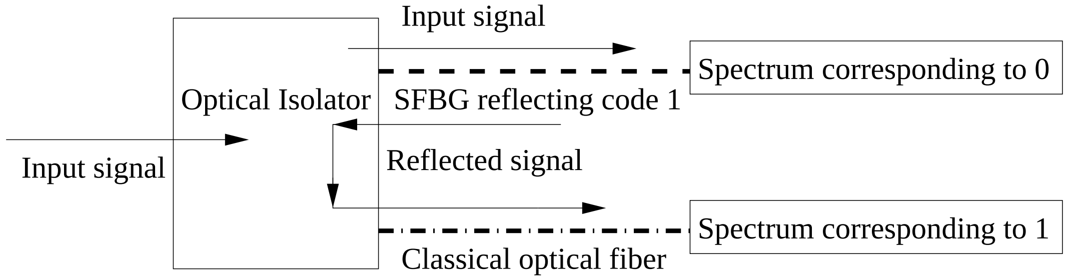

Figure 2: Code separator device.

3.2 SFBG modeling

We assume that, for any wavelength λ (in micrometers (μm)) in a considered transmission band [$\lambda_{\min}$, $\lambda_{\max}$], there exist only two counter-propagating guided modes in the SFBG of respective amplitudes $A(.)$ and $B(.)$. We denote by n_{eff} the unperturbed refractive effective index and by β the propagation constant of the fiber. The perturbation by UV exposure, denoted by δn_{eff}, of the refractive effective index along the fiber is given by [21]:

$$\delta n_{\text{eff}}(z) = \overline{\delta n_{\text{eff}}}(z)\left(1 + \nu\cos\left[\frac{2\pi}{\Theta}z + \phi(z)\right]\right) \tag{10}$$

where $z \in [-\frac{L}{2}, \frac{L}{2}]$, L is the fiber length in millimeters (mm), Θ is the nominal grating period (μm), $\overline{\delta n_{\text{eff}}}(z)$ is the slowly varying index amplitude change over the grating (also called apodization) which is periodic of period P (mm), ν is the fringe visibility and $\phi(z)$ is the slowly varying index phase change (also called chirp).

Here, in order to obtain SBFGs easy to build, we consider fibers with no chirp (i.e. $\phi(z) = 0$). Furthermore, for sake of simplicity, the fringe of visibility $\nu = 1$.

While the modes are orthogonal in an ideal waveguide and therefore do not exchange energy, the presence of a dielectric perturbation causes the modes to be coupled. Introducing the detuning parameter:

$$\zeta = \beta - \frac{\pi}{\Theta} = \frac{2\pi n_{\text{eff}}}{\lambda} - \frac{\pi}{\Theta}$$

and the new unknowns:

$$R(z) = A(z)\exp(i\zeta z - \tfrac{\phi(z)}{2}),$$
$$S(z) = B(z)\exp(-i\zeta z + \tfrac{\phi(z)}{2})$$

the coupled equations can be written as:

$$\frac{dR}{dz}(z) = i\hat{\sigma}(z)R(z) + i\kappa(z)S(z), \tag{11}$$

$$\frac{dS}{dz}(z) = -i\hat{\sigma}(z)S(z) - i\overline{\kappa}(z)R(z). \tag{12}$$

When δn_{eff} is small compared to n_{eff}, the two coupling coefficients can be approximated by: $\hat{\sigma}(z) = \zeta + \beta\frac{\overline{\delta n_{\text{eff}}(z)}}{n_{\text{eff}}} - \frac{1}{2}\frac{d\phi}{dz}(z)$ and $\kappa(z) = \frac{\nu}{2}\beta\frac{\overline{\delta n_{\text{eff}}(z)}}{n_{\text{eff}}}$.

This system, known as the 'two modes coupling' model, is completed by the following boundary conditions: $R(-\frac{L}{2}) = 1$ (the forward-going wave is incident from $-\infty$) and $S(\frac{L}{2}) = 0$ (there is no backward-going wave for $z \geq \frac{L}{2}$).

The main characteristic of a SFBG is then expressed through its power reflection function r defined as:

$$\lambda \mapsto r(\lambda) = \left|\frac{S(-\frac{L}{2})}{R(-\frac{L}{2})}\right|^2. \tag{13}$$

Equations (11)-(12) can be solved by using a simplified transfer matrix method [4]

4 Optimization problem

4.1 Definition of the inverse problem

We consider a CDMA code generated by N_{code} wavelengths $\Lambda = (\lambda_i)_{i=1}^{N_{\text{code}}}$ (μm). The set of wavelengths corresponding to code of the bit '1' for a particular user 'A' is defined by:

$$\Lambda_A = \{\lambda_i | i = 1...N, N \leq N_{\text{code}}, \lambda_i \in \Lambda\}. \tag{14}$$

Due to the fact that the considered SFBG introduced in previous section can only generate symmetrical spectra [10], we will generate a SFBG that reflects also the symmetrical wavelengths of Λ centered around the wavelength λ_c. This new set of wavelengths is denoted by Λ_{A,λ_c}

This problem can be reformulated considering that each SFBG with no chirp can be characterized by its apodization $z \mapsto \overline{\delta n_{\text{eff}}}(z)$. Denoting by Ω_{apo} the associated search space of all acceptable apodization profiles, we define the cost function h_0 as:

$$h_0(x) = \int_{[\lambda_{\min},\lambda_{\max}]} (r(x)(\lambda) - r_{\text{target}}(x)(\lambda))^2 d\lambda \tag{15}$$

where $r(x)(.)$ is the power reflection function (13) of the SFBG with an apodization associated to $x \in \Omega_{\text{apo}}$ and $r_{\text{target}}(x)$ the nearest perfect power reflection function to $r(x)$ matching the desired requirements.

We must include some restrictions on Ω_{apo} in order to find a SFBG with an apodization profile with some 'interesting' characteristics for practical implementation (otherwise it requires a high-level and expensive mastering of the writing process): A low number of π-phase shifts (sign changes in the profile), a smooth profile and a maximum index variation $\overline{n}_{\max}$ inferior to 5.10^{-4}. Thus, apodization profiles are generated by spline interpolation through a reduced number of N_S points equally distributed along the first half of the sampling pattern and completed by parity. We will choose a value of N_S high enough to ensure a large number of peaks in the spectral response but small enough to ensure a profile easy to implement.

Thus, the corresponding search space of the optimization problem is a hypercube:

$$\Omega_{N_S} = [-\overline{n}_{\max}, \overline{n}_{\max}]^{N_S}, \tag{16}$$

where $\overline{n}_{\max}$ is a design constraint.

The discrete version of the cost function h_0 on Ω_{N_S} is defined by:

$$h_{0,N_c}(x) = \sum_{i=1}^{N_c-1} \frac{(\lambda_{i+1} - \lambda_i)}{2}\Big((r(x)(\lambda_{i+1}) - r_{\text{target}}(x)(\lambda_{i+1}))^2 + (r(x)(\lambda_i) - r_{\text{target}}(x)(\lambda_i))^2\Big). \tag{17}$$

In the above expression, the power reflection function $r(x)$ of the SFBG with an apodization associated with $x \in \Omega_{N_S}$ is evaluated on N_c wavelengths equally distributed on the transmission band $[\lambda_{\min}, \lambda_{\max}]$ by using the simplified transfer matrix method [4]. Furthermore, $r_{\text{target}}(x)$ denotes the nearest perfect power reflection function to $r(x)$ reflecting the wavelength in Λ_{A,λ_c} with a transmission rate greater than 0.95 (enough for industrial applications):

$$r_{\text{target}}(x)(\lambda) = \begin{cases} \max(0.95, r(x)(\lambda)) \; if \; \lambda \in \Lambda_{A,\lambda_c} \\ 0 \text{ elsewhere} \end{cases} . \tag{18}$$

Thus the SFBG design problem can be formulated as the following optimization problem:

$$\begin{cases} \text{Find } x \in \Omega_{N_S} \text{ such that} \\ h_{0,N_c}(x) = \min_{x \in \Omega_{N_S}} h_{0,N_c}(x). \end{cases} \tag{19}$$

4.2 Parameters in algorithms

We consider a CDMA code generated by $N_{\text{code}} = 8$ wavelengths: $\lambda_1 = 1.5521\mu m$, $\lambda_2 = 1.5473\mu m$, $\lambda_3 = 1.5481\mu m$, $\lambda_4 = 1.5489\mu m$, $\lambda_5 = 1.5497\mu m$, $\lambda_6 = 1.5505\mu m$, $\lambda_7 = 1.5513\mu m$, $\lambda_8 = 1.5521\mu m$. The code corresponding to '1' for the user 'A' is defined by: $\Lambda_A = [\lambda_1, \lambda_3, \lambda_4, \lambda_7, \lambda_8]$. Thus we are interested to generate a SFBG that reflects Λ_{A,λ_c} with $\lambda_c = 1.5525\mu m$.

The SFBG characteristics are set to $n_{\text{eff}} = 1.45$, $L = 100$mm, $P = 1.039$mm and $\Theta = 0.53\mu$m. The SFBG apodization profile are generated by $N_S = 9$ interpolation points with $\overline{n}_{\max} = 5.10^{-4}$ and the functional (17) is evaluated considering $N_c = 1200$ wavelengths in the transmission band $[1.545\mu\text{m}, 1.56\mu\text{m}]$. Those values have given good results (profiles easy to implements) considering the problem of designing a multichannel filter of 16 peaks [10].

In order to solve problem (19) considering those values, we use the SDA of Section 2.2 with the following parameters:

The steepest descent algorithm [18] is used as the core optimization algorithm. We use the two-layer algorithm A_2 (i.e. $i = 2$) with $t_0 = 10$, $t_{l_1} = 5$, $t_{l_2} = 5$ and $\epsilon = -\infty$ (i.e. the algorithm runs until the given complexity). The initial point v_1 for A_2 is generated randomly in Ω_{N_S}. The gradient of h_{0,N_c} used in A_0 is approximated using finite difference approximations. This algorithm applied with this set of parameters has been validated on various benchmark test cases [9] and industrial applications [13, 14, 11, 7, 3, 8], in particular for the design of pass-band and multichannel filters [10].

4.3 Numerical results and discussion

Figure 3 shows the apodization profile and the associated power reflection function obtained with the SDA. The initial and final cost function h_{0,N_c} are equal to 12.84 and 2.09, respectively. The total number of functional evaluations is about 3000. SDA optimization takes about 10 hours. The optimized SFBG presents two interesting characteristics:

- As we can observe on Figure 3-Right, the optimized spectrum corresponds to a good approximation of the target spectrum. Furthermore, the inter-channel and out-of-band rejection (undesirable side peaks) is inferior to 0.3 which is an acceptable level for practical application.
- The optimized apodization profile (see Figure 3-Left) is suitable for practical implementation. Indeed, the number of necessary π-phase shifts is 5 (a number easy to implement [10]), the index modulation of the profile is homogeneously distributed along the pattern and the maximum amplitude of the profile is 2.10^{-4}.

5 Conclusion

A particular configuration of CDMA filter based on non-chirped SFBG have been designed by a semi-deterministic optimization algorithm. The grating solution produced by the semi-deterministic approach exhibits good characteristics for practical implementation because it has no step variation, a low maximum index modulation value and a small number of π-phase shifts in the sampling pattern. A prototype of this fiber will be developed by the "Southern Electronic Institute" at "Montpellier University".

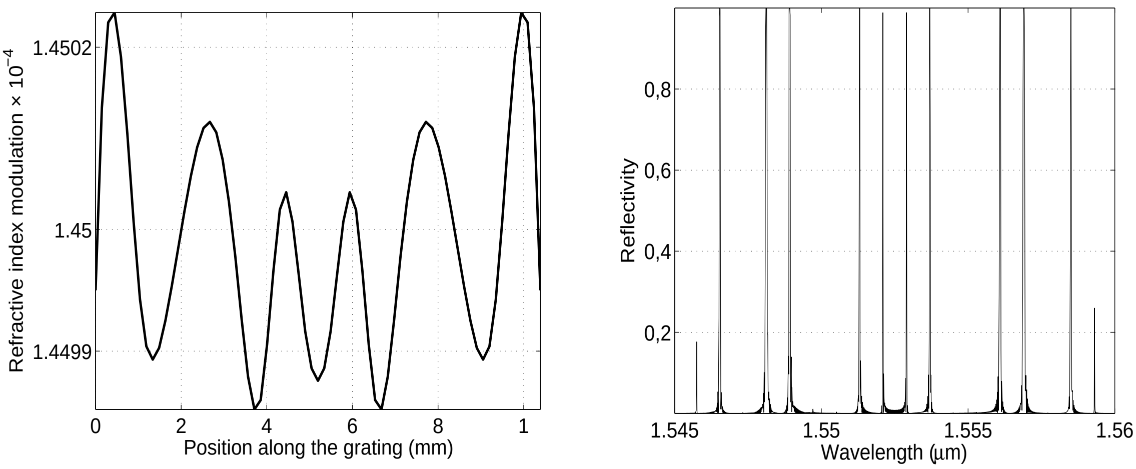

Figure 3: Optimized apodization profile (**Left**) and associated spectrum (**Right**).

Acknowledgments

This work was carried out with financial support from the french "Centre National de la Recherche Scientifique", the "Institut de Mathématiques et de Modélisation de Montpellier" and the "Institut d'Electronique du Sud" under the MATH-STIC project No. 80-0237; the Spanish "Ministry of Education and Science" under the projects No. MTM2007-64540 and "Ingenio Matematica (i-MATH)" No. CSD2006-00032 (Consolider-Ingenio 2010); and the "Dirección General de Universidades e Investigación de la Consejería de Educación de la Comunidad de Madrid" and the "Universidad Complutense de Madrid" in Spain, under the project No. CCG07-UCM/ESP-2787.

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