Proceeding of the 2015 9th International Conference on Telecommunication Systems Services and Applications, TSSA 2015

Country United States - SIR Ranking of United States

4

H Index

Subject Area and Category
Computer Science
- Artificial Intelligence
- Computer Science Applications
- Signal Processing

Engineering
- Control and Systems Engineering

Publisher

Publication type Conferences and Proceedings

ISSN -

Coverage -

Scope Information not localized

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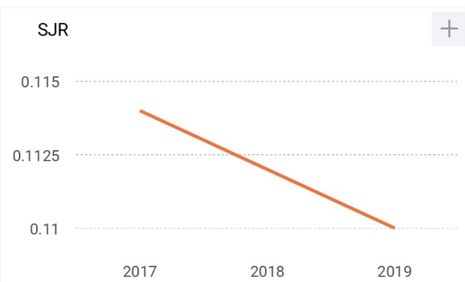

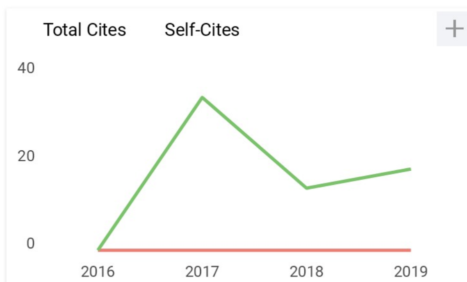

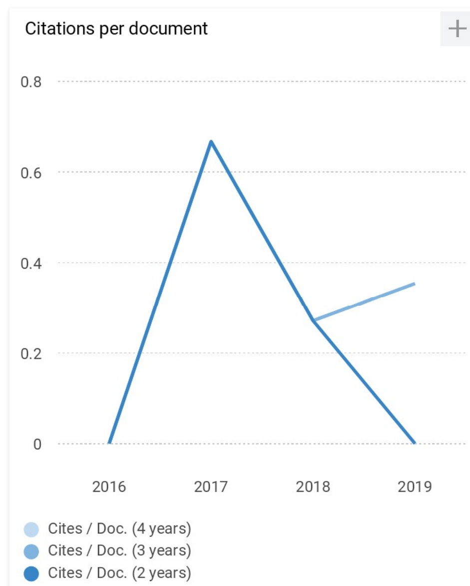

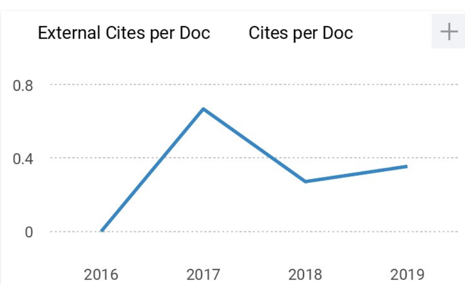

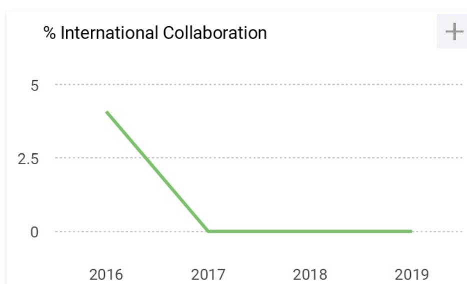

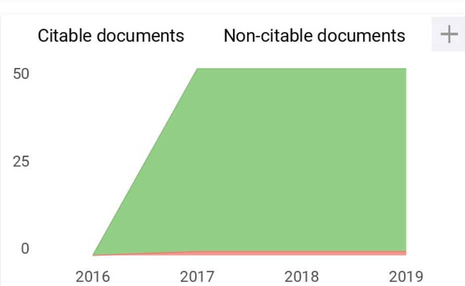

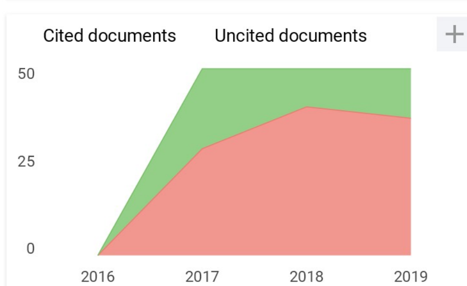

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Proceeding of

2015 9th International Conference on Telecommunication Systems Services and Applications (TSSA)

November 25-26, 2015
Bandung, Indonesia

ISBN (XPLORE COMPLIANT): 978-1-4673-8447-6
ISBN (CD-ROM): 978-1-4673-8445-2
ISBN (Print): 978-1-4673-8446-9

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The Effects of Apodization profile on uniform Fiber Bragg Gratings

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***Abstract*— the sensing applications of fiber Bragg gratings (FBGs) offer a high sensitivity, as well as other important advantages, such as real-time processing, long-term stability, immunity to electromagnetic interference, and convenient multiplexing capabilities. The reflection spectrum of fiber Bragg gratings with a uniform modulation of the refractive index is accompanied by series of sidelobes at the adjacent wavelength. It is very important to minimize and, if possible, eliminate the reflectivity of these sidelobes. The design of fiber Bragg gratings used Coupled Mode Theory. The coupled mode equations were solved by the Transfer Matrix Method since it was considered as good approximation to calculate the spectral response of fiber Bragg gratings. Apodization techniques are used to get optimized reflection spectrum. . The uniform FBGs with several types of apodization were modeled in this project. It was proven that apodization profile could be reduced the sidelobes. In addition, each profile also has the bandwidth and the maximum reflectivity better than others.**

Keywords*— *maximum reflectivity; fiber Bragg gratings; coupled mode equation; transfer matrix method; apodization

I. Introduction

Fiber Bragg gratings are important component in fiber communication and fiber sensing fields. The FBGs are used extensively in telecommunication industry for dense wavelength division multiplexing (DWDM), dispersion compensation, laser stabilization, and Erbium amplifier gain flattening [1-2]

The apodization is a well known technique used in many FBG application, few literature review deal with optimizing sensor performance using apodized FBGs [3-4]. In this final project, we introduce a comprehensive study on the impact of using different apodization profile (Blackman, Hamming and Raised sine) on the performance of uniform FBGs. The performance evaluation parameters tested in this study are uniform FBGs the reflectivity, sidelobes and full width half maximum (FWHM).

II. Basics Theory

A. The Uniform Fiber Bragg Gratings

A uniform Fiber Bragg Grating is simple FBG where the period and amplitude modulation index change remains constant for the entire gratings length. In common optical fiber, the UV-induced refractive index changes are uniform or non-uniform inside the fiber core and negligible in the cladding. With this assumption, a perturbation to the effective refractive index n_{eff} of the guided mode of interest, expressed as equation (1) [6].

$$\delta n_{eff}(z) = \overline{\delta n_{eff}(z)}\left[1 + s\cos\left(\frac{2\pi}{\Lambda}z + \phi(z)\right)\right] \quad (1)$$

For a uniform, $\overline{\delta n_{eff}}$ is a constant and $\phi(z) = 0$. A typical schematic of uniform fiber Bragg gratings with input and output signal indicated is shown on Figure 4.1

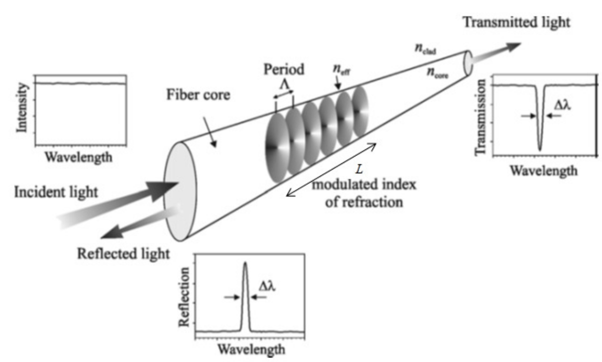

Fig. 1. Illustrating the change induced in the refractive index to create an FBGs in the fiber core [5]

B. Coupled-mode Theory

In this section, we follow the development presented by Gopakumar Sethuraman [7]. The characteristic of the Fiber Bragg Gratings can be understood and modelled by several approach. The most widely used theory is the coupled mode theory[8-9]. The coupled-mode theory is a suitable to describe the propagation of the optical waves in a waveguide with a slowly varying index along the length of the waveguide [10]. The basic idea of coupled mode theory in fiber Bragg gratings (FBGs) is that the grating serves as a perturbation that electrical field of the waveguide with a perturbation can be represented power between the forward and backward moving modes. The transverse component of the electric field at position in the perturbed fiber can be described by a linear superposition of the ideal guided modes of the unperturbed fiber.

. In a uniform Fiber Bragg Gratings having a constant grating period, forward and backward propagating fields are given by coupled mode equation [6-7]:

$$\frac{d}{dz}R(z) = i\hat{\sigma}R(z) + i\kappa S(z) \tag{2a}$$

$$\frac{d}{dz}S(z) = -i\hat{\sigma}S(z) - \kappa R(z) \tag{2b}$$

where, $R(z)$ and $S(z)$ are amplitude of forward wave and amplitude of backward wave.

The general "dc" self-coupling coefficient $\hat{\sigma}$ can be presented by[6][11],

$$\hat{\sigma} = \delta + \sigma - \frac{1}{2}\frac{d\phi}{dz} \tag{3}$$

where $\frac{1}{2}\frac{d\phi}{dz}$ is describe possible chirp of grating period and ϕ is the grating phase. The detuning can be presented [6-7][11]:

$$\delta = \beta - \frac{\pi}{\Lambda} = \beta - \beta_D = 2\pi n_{eff}\left(\frac{1}{\lambda} - \frac{1}{\lambda_B}\right) \tag{4}$$

where $\lambda_B = 2n_{eff}\Lambda$ is the design peak reflection wavelength for a very weak grating, $\delta n_{eff} \to 0$ with a period Λ . For a single-mode Bragg reflection grating, we find the following simple relation [6]:

$$\sigma = \frac{2\pi}{\lambda}\overline{\delta n_{eff}} \tag{5}$$

$$\kappa = \frac{\pi}{\lambda}s\overline{\delta n_{eff}} \tag{6}$$

C. Transfer Matrix Method

The transfer matrix method was first used by Yamada [12] to analysis optical waveguides. This method can also be used to analysis the fiber Bragg problem. The coupled-mode equation (2a) and (2b) can be solved by the transfer matrix method for uniform gratings. Solving coupled mode equation for transfer matrix method (TMM) is found. We can get amplitude reflection ρ of the grating is given by [6-7]

$$\rho(\lambda) = \frac{-\kappa\sinh(\gamma_B L)}{\hat{\sigma}\sinh(\gamma_B L) + j\gamma_B\cosh(\gamma_B L)} \tag{8}$$

where,

$$\gamma_B = \sqrt{\kappa^2 - \hat{\sigma}^2} \tag{9}$$

The power reflection coefficient $R(\lambda)$ can be written by [6-7]:

$$R(\lambda) = |\rho|^2 = \frac{\sinh^2(\gamma_B L)}{\cosh^2(\gamma_B L) - \frac{\hat{\sigma}^2}{\kappa^2}} \tag{10}$$

At the center wavelength of the Fiber Bragg Gratings the wave vector detuning is $\hat{\sigma}$ = 0, power reflection becomes [6]:

$$R(\lambda) = \frac{\sinh^2(\kappa L)}{\cosh^2(\kappa L)} = \tanh^2(\kappa L) \tag{11}$$

D. Apodization Function

Apodization is a variation of modulation depth along the grating length and is used to reduce the side lobes [13]. The apodized fiber grating can be modelled by the coupled mode theory and then using transfer matrix method is used to solve the coupled mode equation.

Several apodization functions was chosen in this thesis. We will choose the best three of the profiles (Blackman, Hamming and Raised sine profile) that are applicable to references that have been done by Ashry [3]. Although apodization is well-known technique used in many applications FBG, this method is expected to optimize the performance of FBG Bandpass Filter. There are examples of several samples apodization profile [5]:

Sinc Profile

$$s(z)=\frac{\sin\left(\frac{2\pi(z-\frac{L}{2})}{L}\right)}{\frac{2\pi(z-\frac{L}{2})}{L}} \quad (12)$$

Blackman Profile

$$s(z)=\left[\frac{1+1.19\cos\left(\frac{2\pi(z-\frac{L}{2})}{L}\right)+0.19\cos\left(\frac{4\pi(z-\frac{L}{2})}{L}\right)}{2.38}\right] \quad (13)$$

Sine Profile

$$s(z)=\sin\left(\frac{\pi z}{L}\right) \quad (14)$$

Raised sine Profile

$$s(z)=\sin^2(\frac{\pi z}{L}) \quad (15)$$

Hamming Profile

$$s(z)=\frac{1+0.9\cos\left(\frac{2\pi(z-\frac{L}{2})}{L}\right)}{1+0.9} \quad (16)$$

Positive-tanh profile ($a=4$)

$$s(z)=\tanh(\frac{2az}{L}) \quad (17)$$

where,

$$0\le z\le L \quad (18)$$

The various apodization profiles are plotted in Figure 3. From the various functions, there are some function whose slope is higher. When we look at the existing references, a function that has a greater slope is able to reduce the sidelobes of the FBG. Figure 3 show that the Blackman profile has the greatest slope. Further, we will optimize the function of the best three from several functions.

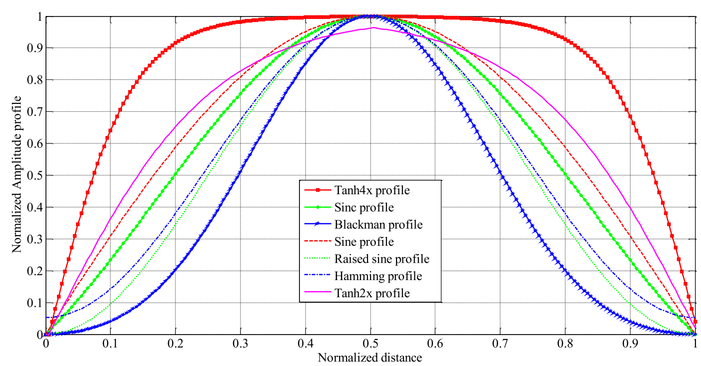

Fig. 2. Several Apodization function

The effect of the apodization in the models of the Bragg gratings can be represented by using z-dependent function $s(z)$ in refractive index. If apodization function is substituted into equation (6), the spectral response of the apodized gratings can be obtained by solving these equations.

III. Simulation Result

In this paper, the simulation will be limited to single-mode silica-based fiber operating at wavelength of 1550 nm. The grating length (L) is within range 1 mm to 16 mm and index change ($\overline{\delta n_{eff}}$) is 0.0004. And then analysis of the different three apodization profile to see in terms of the maximum reflectivity, sidelobes and FWHM.

A. Uniform FBGs with and without Apodized

Based on the equation (11), Fig. 4 show the reflection spectrum on uniform FBGs with and without apodization. The maximum reflectivity apodized grating is reduced slightly (1→0.99), but the sidelobes are suppressed and the ripple is reduced. This is caused by the reduction in the index change on both sides of the gratings.

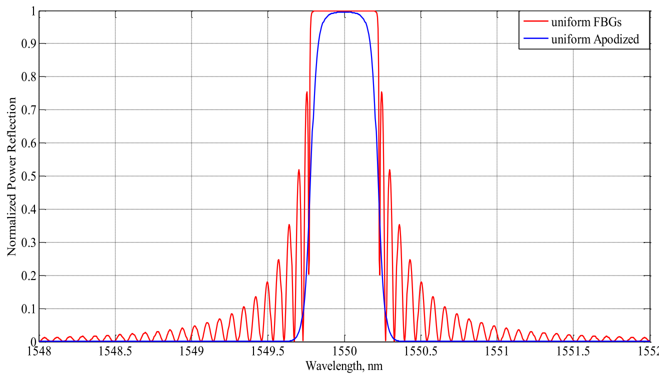

Fig. 3. Reflection spectrum of a uniform FBGs (red solid line) and uniform apodized FBGs (blue solid line).

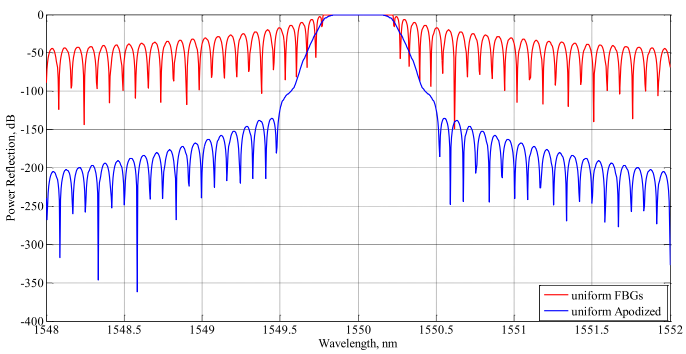

Fig. 4. Reflection spectrum of a uniform FBGs (red solid line) and uniform apodized FBGs (blue dashed line) with power reflection in dB)

B. Apodized Gratings

Based on several reflection spectrum at yield equation (11), we can create a plot of the relationship between the index change versus maximum reflectivity and grating length on several apodized on uniform FBGs. It shows that the maximum reflectivity is increased if the grating length is increased, until it reaches saturation.

Blackman apodized on uniform FBGs

When $L = 9$ mm, the maximum reflectivity reaches 0.9913. This value has been able to meet the specifications when used for bandpass filters. If we look at the value of FWHM in Fig. 7, the smallest bandwidth is when $L \geq 13$ mm. Because the consideration is FWHM and maximum reflectivity, the best option is when $L = 13$. Where the value of the FWHM is 0.428 nm and maximum reflectivity is 0.9994.

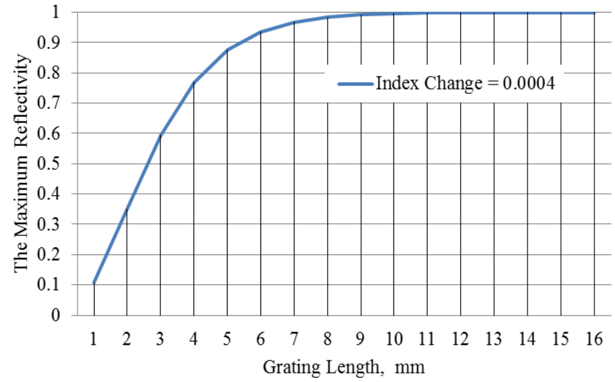

Fig. 5. The maximum reflectivity on Blackman apodized uniform gratings versus length with the index change value is 0.0004.

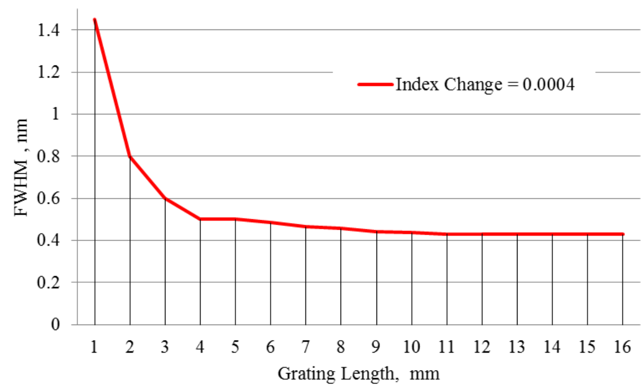

Fig. 6. The FWHM on apodized Blackman uniform gratings versus length with the index change value is 0.0004.

Hamming Apodized on uniform FBGs

When $L = 8$ mm, the maximum reflectivity reaches 0.9957. This value has been able to meet the specifications when used for bandpass filters. Compared to Blackman apodized, Hamming apodized has bigger maximum reflectivity at the same length.

Figure 10 is a plot of the relationship between the full wave at half maximum (FWHM) and grating length on Hamming apodized uniform grating. At the grating length equal to 11 mm, the value of FWHM been constant with a value of 0.428 nm. Because the consideration is the FWHM and the maximum reflectivity, the best option is when L = 11 mm. Where the value of the FWHM is 0.428 nm and maximum reflectivity is 0.9997.

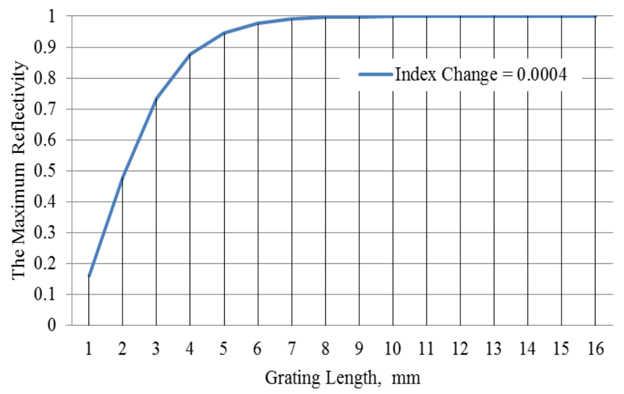

Fig. 7. The maximum reflectivity on Hamming apodized uniform gratings versus length with the index change value is 0.0004.

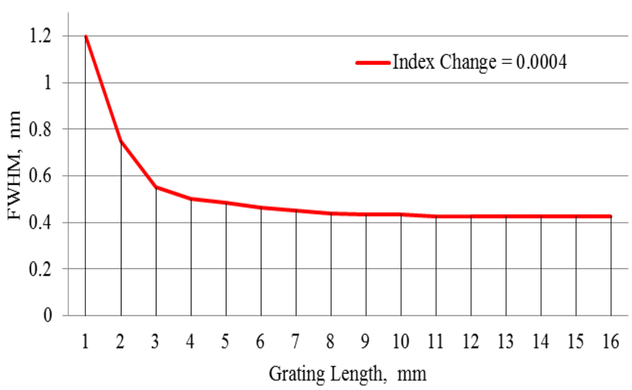

Fig. 8. The FWHM on apodized Hamming uniform gratings versus length with the index change value is 0.0004.

Raised sine Apodized on uniform FBGs

When L = 8 mm, the maximum reflectivity reaches 0.9939. This value has been able to meet the specifications when used for bandpass filters. Compared with Blackman apodized, Raised sine apodized has bigger the maximum reflectivity at the same length but smaller than Hamming apodized.

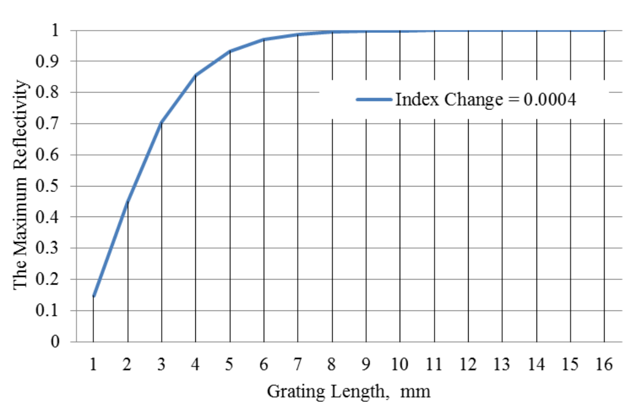

Fig. 9. The maximum reflectivity on Raised sine apodized uniform gratings versus length with the index change value is 0.0004.

Figure 13 is a plot of the relationship between the FWHM and grating length on Hamming apodized uniform grating. At the grating length equal to 13 mm, the value of FWHM been constant with a value of 0.428 nm. Because the consideration is the FWHM and the maximum reflectivity, the best option is when L = 13 mm. Where the value of the FWHM is 0.425 mm and mximum reflectivity is 0.9999.

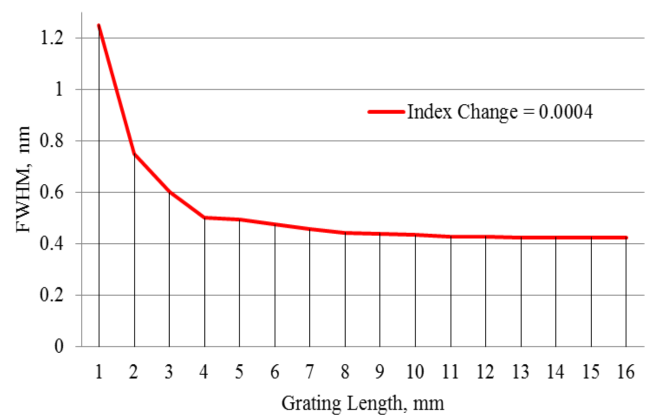

Fig. 10. The FWHM on Raised sine apodized uniform gratings versus length with the index change value is 0.0004.

C. *Comparison of three apodization profile*

The maximum reflectivity of different apodization profile is compared to use a constant grating length, L and index change, $\overline{\delta n_{eff}}$. By using Transfer Matrix Method, we can obtain the reflectivity of each apodized FBG. Result of comparing apodized uniform FBG and uniform FBG, the peak value slightly down and then sidelobes smaller. Based figure 15 and 16, the maximm reflectivity of each apodized profile is summarized in Table I.

FBG is used for sensing applications must have a high reflectivity, low-level sidelobes and narrow FWHM. The results obtained in the two previous sections showed that the Blackman apodized profile has a minimum level of sidelobes but the peak value is lower than the other.

The apodization has a significant impact on reducing the sidelobes found in uniform FBG. The sidelobes level reductions caused by different apodization profile are illustrated in Fig. 13, when the reflectivity is represented on logarithmic scale.

TABLE I. COMPARISON APODIZED UNIFORM FBGS

Apodization Profile	**Parameter**		
	Maximum Reflectivity	***Sidelobes***	***FWHM***
Uniform	1	-3.483dB	0.467 nm
Blackman	0.9956	-136.6 dB	0.437 nm
Hamming	0.9992	-77.95 dB	0.435 nm
Raised sine	0.9988	-95.6 dB	0.434

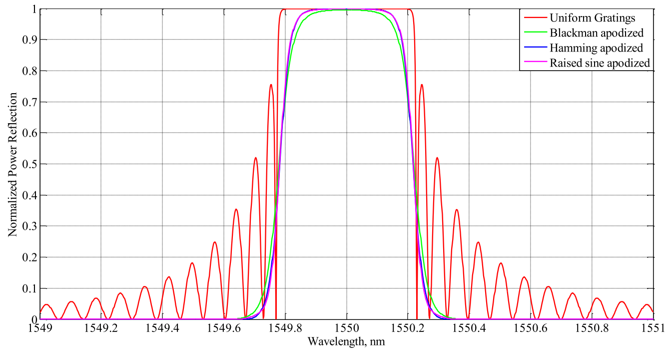

Fig. 11. The reflection spectrum of different apodized uniform FBGs at L = 10 mm and index change = 0.0004.

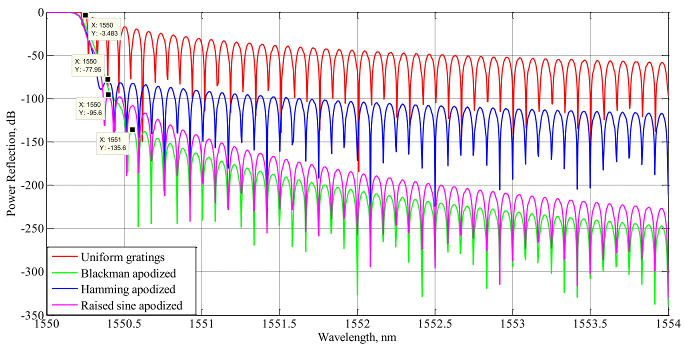

Fig. 12. The reflection spectrum in dB of different apodized uniform FBGs at L = 10 mm and index change = 0.0004.

IV. Conclusion

The evaluation parameter used for comparing apodization profile on uniform FBGs are maximum reflectivity, sidelobes level and FWHM. The maximum reflectivity and FWHM are relatively similar, but sidelobes are suppressed and the ripple is reduced.

For Blackman apodized profile with index change ($\overline{\delta n_{eff}}$) equal to 0.0004, the results of the optimization at L = 13 mm, has a maximum reflectivity = 0.9994, the FWHM = 0.428 nm and sidelobes = -131.4 dB. For Hamming apodized profile with index change ($\overline{\delta n_{eff}}$) equal to 0.0004, the results of the optimization at L = 11 mm, has a maximum reflectivity = 0.9997, the FWHM = 0.428 nm and sidelobes = -80.15 dB. For Raised sine apodized profile with index change ($\overline{\delta n_{eff}}$) equal to 0.0004, the results of the optimization at L = 13 mm, has a maximum reflectivity = 0.9999, the FWHM = 0.425 nm and sidelobes = -90.28 dB

As sensing application, when viewed in terms of the sidelobes, the Blackman apodized profile is the best than Hamming and Raised apodized profile. In terms of FWHM, the Raised sine apodized profile is the best than Blackman and Hamming apodized profile. In terms of the maximum reflectivity, the Hamming apodized profile has the best result.

Acknowledgment

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