

Research Article

Designing of Fiber Bragg Gratings for Long-Distance Optical Fiber Sensing Networks

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Most optical sensors on the market are optical fiber Bragg grating (FBG) sensors with low reflectivity (typically 7-40%) and low side-lobe suppression (SLS) ratio (typically SLS <15 dB), which prevents these sensors from being effectively used for long-distance remote monitoring and sensor network solutions. This research is based on designing the optimal grating structure of FBG sensors and estimating their optimal apodization parameters necessary for sensor networks and long-distance monitoring solutions. Gaussian, sine, and raised sine apodizations are studied to achieve the main requirements, which are maximally high reflectivity (at least 90%) and side-lobe suppression (at least 20 dB), as well as maximally narrow bandwidth (FWHM<0.2 nm) and FBGs with uniform (without apodization). Results gathered in this research propose high-efficiency FBG grating apodizations, which can be further physically realized for optical sensor networks and long-distance (at least 40 km) monitoring solutions.

1. Introduction

The manufacturing process of fiber Bragg grating (FBG) technology is relatively simple, and such sensors have a lot of technological advantages, for instance, the realization of passive components, resistance to electromagnetic interference (EMI) and corrosion, small size, high accuracy, and multiplexing abilities. FBG is one of the most utilized and progressing optical sensor solution technologies. Mainly, optical FBG sensors are used to detect objects or environmental temperature, induced strain, applied pressure, and vibration [1–4].

As an alternative to optical sensors, electrical sensors can be mentioned, but their performance can be negatively affected by high voltage and the presence of the electromagnetic field–electromagnetic interference. Due to the previously mentioned, depending on the measurement location, it can be difficult or even impossible to realize the use of electrical sensors. Another major disadvantage of electrical sensor realization is that such sensors require a consistent supply of electrical energy, but it might be challenging to provide electricity to remote sensor locations if there is no available source nearby. In contrast, fiber optical sensors are passive devices that do not require electricity since optical fiber is made from a dielectric material. In these situations, the use of fiber optical sensors is a suitable solution [5].

A vital field where FBG technology has rapidly improved over the years is structural health monitoring (SHM for various constructions such as roads, bridges, railroads, dams, buildings, and aircraft) as well as in medicine, oil and gas industries, and security solutions [6, 7]. FBGs can be applied in time and wavelength multiplexing technologies and operate as optical filters, dispersion compensation modules, and sensor solutions.

Multiple FBGs can be combined on a single optical fiber, allowing FBG sensor systems to use and read many sensors simultaneously, reducing the number of fibers used and



FIGURE 1: Structure and working principle of FBG sensors.

simplifying their installation. FBG sensors can be successfully combined with fiber optical data transmission systems [2]. An important prerequisite for the design of optical sensor networks is to choose a sufficiently efficient channel spacing to maintain the highest possible spectrum efficiency of the sensor network and to avoid overlapping of the optical signals that might be observed between adjacent optical sensors if their reference wavelengths/frequencies are configured too close to each other.

As the demand for FBG sensors in various applications grows, it is increasingly important to optimize and customize their configuration and parameters, so there are available different types of FBG sensors that vary in their structure, construction, and design techniques. Therefore, it is essential to research different FBG types and evaluate their specific advantages and disadvantages to define optimal sensor types and their parameters (especially for sensor networks) to ensure the realization of specific applications where they are utilized.

FBGs are formed by incorporating specific changes in the refractive index modulation of the optical fiber core components that are based on the diffraction grating principle. When a light signal is transmitted through such a grating structure in an optical fiber, some part of the light is reflected from each grating plane (see Figure 1). Each part of the reflected light combines to form one unified reflected beam of light, and this is possible only if the Bragg condition described by the equation is fulfilled:

$$\lambda_B = 2 \bullet \Lambda \bullet n_{\text{eff}},\tag{1}$$

where Λ is the grating period that determines the distance between two adjacent grating planes, n_{eff} is the effective refractive index of the fiber core, and λ_B is the Bragg wavelength.

When the Bragg condition is fulfilled, the reflected light forms a backward reflected peak with a central wavelength known as λ_B . Such a grating structure, developed by the Bragg relation, acts as a mirror that reflects the wavelength



FIGURE 2: Typical reflected optical spectrum and main parameters of the FBG signal [5].

 λ_B and transmits the rest of the optical signal further inside the optical fiber [5, 8, 9].

Two quantities determine the characteristics of the FBG, which are the grating strength (also known as the modulation depth) and the grating length. However, in general, three main parameters must be controlled while designing the fiber Bragg gratings, and these are reflectivity (%), bandwidth (nm), and SLS (dB).

The full width at half maximum (FWHM) is the bandwidth of the reflected signal at a -3 dB power level. This bandwidth depends on several parameters, especially the grating length. Most sensor applications have an average FWHM bandwidth of 0.05 nm to 0.4 nm, but for some sensors, it may even exceed 1 nm [5]. Figure 2 shows a typical peak of the reflected FBG signal spectrum, where SLS and FWHM parameters are shown. Reflected optical signal bandwidth directly depends on the grating strength; therefore, the grating strength can be used to adjust the signal's bandwidth. The grating length can be configured to improve the reflectivity of the signal because reflectivity depends on the grating strength and the grating length. The reflectivity of the signal can be calculated by using the equation:

Reflectivity
$$[\%] = 10^{P_{\text{max}}} [\text{dB}]/10 \bullet 100,$$
 (2)

where P_{max} is the maximal signal power (dB) of the reflected signal spectrum.

Apodized gratings for the FBGs' design offer a significant improvement in side-lobe reduction while maintaining reflectivity as well as the narrow bandwidth of the signal. Several apodization functions are typically used, such as Gaussian, sine, raised sine, hyperbolic tangent, Nuttall, and other types of apodizations [10–12]. However, side lobes are a type of unwanted additional distortions of the reflected signal that cannot fully be efficiently controlled with just such a simple grating optimization; thus, additional improvements for the apodization design has to be done as proposed in this research. Such side lobes can be observed in an optical spectrum when the modulation of the refractive index is constant throughout the length of the FBG and then rapidly changes to zero outside the grating range.

It is important to highlight that based on the apodization technique, the modulation of the refractive index is uniformly increased and uniformly reduced along the length of the fiber Bragg grating. However, in this configuration, an increase in total grating length may be required to reach a certain peak (reflectivity) of the reflected signal.

As explained further in this research, the specified optimal FBG parameters for sensor networks are maximally high SLS (at least 20 dB) and maximally narrow bandwidth (FWHM <0.2 nm), but for long-distance monitoring solutions, maximally high reflectivity (at least 90%) and appropriate SLS (at least 20 dB). Based on these requirements, specific FBG sensor gratings are designed and described in the following Sections 2 and 3 of this article.

2. Mathematical Modelling and Design of Fiber Bragg Gratings

The characteristics of the fiber Bragg grating were studied in the simulation environment using *Optiwave Systems* "*Opti-Grating*" software [13]. This software uses the coupled mode theory to model the light and enable analysis and synthesis of gratings. A complex grating is determined by a sequence of uniform segments and analyzed by connecting the segments with the well-known transfer matrix method. This gives the designer the information needed to test and optimize grating designs for specific purposes. In simulation software, it is possible to set and change such grating parameters such as grating shape, average index modulation, period chirp, and apodization type.

Coupled mode theory method suggests that the modes of the unperturbed or uncoupled structures should be the first for defining and solving. Afterward, by realizing analytical methods, the derived coupled mode equations can be solved. The theory proposes that linear superposition of the modes of the unperturbed structures represents the coupled structures. Such assumption provides an insightful and accurate enough mathematical description of electromagnetic wave propagation in various practical situations. This theory provides the means for analysis of near resonance guided mode interaction. In addition, transfer matrix method (TMM) can be used for coupled mode equation solving if the application (device) has multiple grating plus phase shifts. TMM can also be utilized for analysis of almost periodic gratings.

TMM suggests that the whole grating structure is divided into a number of uniform grating sections (having an analytic transfer matrix). By multiplying the individual transfer matrices, the entire structure of the transfer matrix can be gathered [14]. For all *OptiGrating* simulations performed, the typical

For all *OptiGrating* simulations performed, the typical parameters of single mode optical fiber with a core diameter of 9 μ m and a cladding diameter of 125 μ m were set. Each grating central wavelength of the FBG is set to 1550 nm, and the number of segments (planes) is set to 25.

Various FBG reflected signal spectrums at different grating parameters were obtained. Each apodization type of the FBG was analyzed at different grating lengths from 1 mm to 20 mm at different grating modulation indexes (fiber core reflection index changes) $\Delta n = 0.5 \times 10^{-4}$, 1×10^{-4} , 1.5×10^{-4} , and 2×10^{-4} (also observable in Figure 3). Uniform (without apodization), Gaussian, sine, and raised sine apodizations are studied in this phase. These apodizations are described with the following mathematical function:

Gaussian apodization :
$$\Delta n(x) = \Delta n \cdot \exp\left\{-\ln\left(2\right) \cdot \left(\frac{2 \cdot (x - (L/2))}{s \cdot L}\right)^2\right\},$$
(3)

Sine apodization :
$$\Delta n(x) = \Delta n \cdot \sin\left(\frac{\pi \cdot x}{L}\right)$$
, (4)

Raised sine apodization :
$$\Delta n(x) = \Delta n \cdot \sin^2\left(\frac{\pi \cdot x}{L}\right)$$
, (5)

where *L* is the grating length, *s* is the taper length = 0.5, and *x* is the coordinate of light that is propagation along the length of the grating $(0 \le x \le L)$.

Figure 3 depicts the example of our mathematically generated geometrical shapes of the FBG uniform, Gaussian, sine, and raised sine apodization profiles. Geometrical shapes are illustrated when the grating length of the FBG is 10 mm, the grating modulation index $\Delta n = 1.5 \times 10^{-4}$, and the number of segments (planes) is 25.

Several parameters (reflectivity, FWHM, and SLS) of the reflected signal spectrum were determined during the analysis of the data obtained in the simulation results and are discussed in the results section. The reflectivity, side-lobe power, and the FWHM values of the reflected signal were analyzed from all of the measured spectral data.

3. Results and Discussion

The data (reflectivity, FWHM, and SLS) from the obtained reflected signal spectra are summarized in the tables and



FIGURE 4: Reflected signal spectra of the FBG with raised sine apodization ($\Delta n = 1.5 \times 10^{-4}$) and various grating lengths.

1549.8

1549.6

1550

Wavelength (nm)

L = 10 mm

L = 13 mm

provided online on the open repository platform Zenodo [15]. All of this data is included and visually presented in Figures 4-11. Figure 4, for instance, shows the reflected signal spectrum of the FBG optical sensor that uses raised sine apodization when grating lengths (in figure marked as "L") are 4, 7, 10, and 13 mm and the modulation index is $\Delta n = 1.5 \times 10^{-4}$. By increasing the grating length, reflectivity also increases (at L = 4 mm, P_{max} = -6 dB \rightarrow reflectivity is 25% but for 13 mm, 90%), and spectral bandwidth becomes narrower (at L = 4mm, FWHM = 0.328 nm, but if L = 13 mm, FWHM is

-40-50 -60 -70

1549.2

1549.4

L = 4 mmL = 7 mm

> 0.173 nm). Figure 5 shows the reflected signal spectrum comparison between the FBGs with uniform, Gaussian, sine, and raised sine apodizations when the grating length is 13 mm and modulation index $\Delta n = 1.5 \times 10^{-4}$ is used. As we can see in Figure 5, the most efficient spectral deployment of FBG sensors is achieved if uniform FBGs are used. As for the side-lobe parameter, it is best minimized by using raised sine apodization, but after that by utilizing the Gaussian apodization.

1550.2 1550.4 1550.6 1550.8

As it can be observed, Figure 6 clearly shows the coherence between reflectivity, grating length, and grating



FIGURE 5: Comparison between the reflected signal spectra of FBGs with uniform, Gaussian, sine, and raised sine apodizations $(\Delta n = 1.5 \times 10^{-4} \text{ and fixed grating length 13 mm}).$

modulation index of FBG gratings. By increasing the length of the grating, also FBG reflectivity in % increases. The highest reflectivity is reached with uniform (without apodization) realization, then follows sine apodization, after that Gaussian apodization, but the relatively lowest reflectivity is by using the raised sine apodization. From the results, it can be concluded that the use of modulation index $\Delta n = 0.5 \times 10^{-4}$ provides relatively the lowest performance because the reflectivity of 90% is not reached (in the grating length range of 1-20 mm). The highest reflectivity we can observe at higher modulation index values, hence 1.5×10^{-4} and 2×10^{-4} . With higher modulation index values, it is possible to achieve preferred reflectivity while using a shorter length of the specific grating.

While analyzing the signal bandwidth, it can be seen in graphs (see Figure 7) that by increasing the grating length, the value of FWHM decreases. The most rapid changes are observed for the FBGs with 1-5-millimeter-long grating length. When the grating length of 2 mm is used, the FWHM bandwidth is reduced by half compared to the 1 mm long grating. For example, FWHM is 0.74 nm wide when 1 mm uniform grating is chosen, but the grating length of 2 mm (for the same uniform grating) leads to FWHM of 0.38 nm (at modulation index 1×10^{-4}). From the results, it can be concluded that the grating length from 1 to 5 mm is not suitable for sensor networks because it operates with relatively wide bandwidths. Hence, to save the available optical frequency spectrum and use the planned operational optical frequency range more efficiently, larger grating lengths for FGBs should be chosen, thus operating with narrower FWHMs. In Figure 7, it can be seen that the narrowest FWHMs are obtained when applying the lowest modulation index values of 0.5×10^{-4} . It is also important to highlight that for all the apodizations, there are specific values of grating lengths at which an additional increase of grating length does not provide a significant FWHM decrease anymore. For instance, as for the uniform type, significant FWHM decrement is observable until grating lengths of 6-8 mm, while for Gaussian and sine 8-10 mm, and raised sine 10-12 mm. After those values, an increase in grating length does not highly affect FWHM values.

As shown in Figure 8, by analyzing the results obtained from simulations of FBGs with uniform and Gaussian apodization, the SLS is evenly decreased by increasing the grating length from 1 mm to 20 mm when using all four modulation index values $(0.5 \times 10^{-4} \text{ to } 2 \times 10^{-4})$.

When using sine and raised sine apodization with modulation index $(1.5 \times 10^{-4} \text{ and } 2 \times 10^{-4})$, graphs show the decrease of SLS when increasing the used grating length; however, at certain values (as can be seen in Figure 8(c)), the SLS also starts to increase with further increase of grating length. Yet this process can be observed for specific grating lengths, and then again, by increasing the grating length even further, SLS starts to decrease again (function is periodical). We can see similar tendencies in a scientific article [16], where a higher modulation index of 4×10^{-4} is used and well seen when the SLS function is periodical. The lowest SLS values are recorded for uniform FBG (without apodization) where they do not reach the defined threshold (20 dB); thus, we can state that it is not most suitable for FBG sensor networks and long-distance monitoring applications. When applying Gaussian, sine, and raised sine apodizations, side-lobe suppression is significantly improved compared to the uniform profile.

To better analyze and compare the FBG parameters like reflectivity (Figure 9), SLS (Figure 10), and FWHM (Figure 11) and their relation with the apodizations profiles, the comparison was performed with a modulation index of 1.5×10^{-4} . As we can see in Figure 9, while applying gratings in the range between 1 mm and 20 mm, the highest reflectivity results can be ensured by using the uniform profile. As for the second-highest – by sine apodization provide similar results compared to each other and show relatively lower reflectivity when 1 mm to 20 mm grating lengths at modulation index 1.5×10^{-4} are chosen.



FIGURE 6: Continued.



FIGURE 6: Reflectivity versus grating length of FBG with (a) uniform, (b) Gaussian apodization, (c) sine apodization, and (d) raised sine apodization.



FIGURE 7: Comparison of FWHM versus grating length of FBG with (a) uniform, (b) Gaussian, (c) sine, and (d) raised sine apodization.

As we can see in Figure 10, Gaussian apodization ensures the highest SLS (33 to 38 dB) results when 1 mm to 7 mm grating lengths are chosen, but when grating lengths are between 9 mm to 20 mm, the best SLS results (30 to 32 dB) are shown by raised sine apodized FBGs. Uniform fiber Bragg grating provides the least side-lobe suppression values when grating lengths are used in the range of 1 mm to 20 mm.



FIGURE 8: Continued.



FIGURE 8: FBG side-lobe suppression versus grating length of FBG with (a) uniform, (b) Gaussian, (c) sine, and (d) raised sine apodization.



FIGURE 9: Reflectivity versus the grating length of FBG.



FIGURE 10: Side-lobe suppression versus the grating length of FBG.



FIGURE 11: The full width at half maximum versus the grating length of FBG.

TABLE 1: Optimal FBG grating parameters for raised sine, Gaussian apodization, and sine apodization with modulation index 1×10^{-4} , 1.5×10^{-4} , and 2×10^{-4} .

Apodization type	Modulation index (×10 ⁻⁴)	Grating length (mm)	Reflectivity (%)	FWHM (nm)	SLS (dB)
Raised sine	1.0	20	90.3	0.112	35.6
	1.5	13	90.0	0.173	35.7
	2.0	10	90.4	0.228	35.4
Gaussian	1.0	19	90.0	0.110	26.0
	1.5	14	93.1	0.160	24.7
	2.0	10	91.7	0.216	26.9
Sine	1.0	16	90.9	0.118	20.1
	1.5	11	91.9	0.176	20.7
	2.0	13	99.0	0.210	22.5

While analyzing the signal spectral bandwidth, it can be seen in graphs (see Figure 11) that by increasing the grating length, the value of FWHM decreases. The most rapid changes are observed for the FBGs with 1-6 mm long grating length. To save the optical frequency spectrum band, larger grating lengths (at least 6 mm) for FGBs should be chosen, thus operating with narrower FWHMs. The narrowest bandwidth when grating lengths are chosen between 1 mm and 7 mm is provided by uniform FBGs and then by sine and Gaussian apodizations. As for the gratings between 8 mm and 20 mm in length, the narrowest bandwidth can be reached by applying the Gaussian and then sine apodizations.

To provide FBG with narrower bandwidth (FWHM<0.2 nm) and high reflectivity (at least 90%), larger grating lengths for FGBs should be chosen. However, long FBG gratings do not always guarantee higher SLS parameter values. Due to that, it is vital to estimate optimal FBG parameters for every grating type as it is shown in the next paragraph.

Table 1 summarizes the most optimal FBG grating and apodization parameters evaluated from the previously men-

tioned data and graphs. This table does not include previously mentioned uniform type FBG data because results gained by uniform FBGs do not comply with the SLS threshold (at least 20 dB) requirements. As we can see from the Table 1 data, the raised sine apodization provides relatively similar reflectivity and FWHM as does Gaussian apodization, but SLS values are significantly better for raised sine apodization than they can be observed from Gaussian apodization. Based on the research data, raised sine apodization is most optimal for the usage of sensors networks and longdistance monitoring, because overall, the relatively highest quality parameters for the grating can be reached with this type of apodization when mentioned modulation indexes are used. The length of the grating can be reduced when applying higher modulation indexes. However, a higher modulation index increases the spectral band and thus the FWHM value of an FBG.

The relatively best FBG results (reflectivity=90.3%, FWHM=0.112 nm, and SLS=35.6 dB) are observed for raised sine apodization with a modulation index 1×10^{-4} and grating length of 20 mm.



FIGURE 12: Reflected optical signal spectrum of the developed 40 FBG sensor network, where optimal grating parameters are used.



FIGURE 13: Simulation setup for testing FBG sensors' operation distance.

The sensor network with 40 FBG sensors in the wavelength band of 1,530 to 1,659 nm (spacing between the sensors is 1 nm) is developed ("OptiGrating" software) based on these FBG parameters to validate the found optimal parameters (raised sine apodization with modulation index 1×10^{-4} and grating length of 20 mm). The reflected optical signal spectrum is shown in Figure 12.

Figure 12. indicates that the developed 40 FBG sensor network has high reflectivity (>90%) and SLS value (~30 dB). SLS values have slightly deteriorated for the sensor network as the adjacent side lobes overlap.

For testing of FBG operation distance, we have firstly developed an additional simulation setup (see in Figure 13) by using *VPIphotonics* mathematical modelling software. In this model, FBG sensors operation distance (SMF fiber distance between optical circulator and FBG sensor network) is measured and tested.

In this simulation setup, the parameters of components are set based on the real parameters of commercial components. The transmitter part of the setup includes an optical broadband light source (BLS) which has full width at half maximum (FWHM) =80 nm in wavelength band of 1510-1590 nm. BLS component's output spectrum is experimentally measured with S-line Scan 800 interrogator and uploaded into this simulation setup. Here, BLS output is connected to the 3-port optical circulator (OC), which is

used for the separation of the optical light flows-transmitted and reflected FBG signals. Insertion loss for OC of direction $1 \rightarrow 2$ and $2 \rightarrow 3$ is 1 dB, but isolation 50 dB. OC port (2) is connected to SMF-28 single mode optical fiber (SMF) line. For SMF, such parameters are set as follows: attenuation: 0.18 dB/km; dispersion: 16 ps/(nm·km); dispersion slope: $0.092 \text{ ps/(nm^2 \cdot km)}$; PMD: $0.04 \text{ ps/}\sqrt{km}$; effective area: $85 \,\mu\text{m}^2$; and nonlinear index: 1.27 (W × km)⁻¹. SMF is connected with FBG sensor network, in which amplitudefrequency response (FBG transmitted and reflected spectrums) and technical parameters such as reflectivity, FWHM, and central frequency are uploaded. FBG sensors' reflected signals are transmitted from OC port $2 \rightarrow 3$ to the optical spectrum analyzer and signal processing unit, in order to analyze the received optical spectrums of the FBG sensors.

Afterward, for testing and validation purposes, such FBG sensor network's setup is then developed in laboratory environment where the architecture of the scheme is the same (see in Figure 14).

However, the specific 40 FBG sensor network with the estimated optimal parameters (that were investigated, developed, and described in the article, see Figure 12) was not physically available in our laboratory. Therefore for the testing and validation purposes, we have here used the FBG setup available for us in the laboratory, FBG sensor network



FIGURE 14: Experimental validation of the developed simulation model in laboratory environment.



FIGURE 15: Experimentally measured reflected signal spectrum of FBG sensors after BTB, 20, 40 and 60 km transmissions.



FIGURE 16: Mathematical simulation's measured reflected signal spectrum of FBG sensor after BTB, 20, 40, and 60 km transmission.



FIGURE 17: Reflected optical signal spectrum of the developed 40 FBG sensor network after BTB, 20, 40, and 60 km transmission.

with 5 FBGs (with central wavelengths of 1541, 1543, 1545, 1547, and 1549 nm).

As we can see in Figures 15 and 16, reflected signal spectrums of FBG sensor networks after BTB, 20, 40, and 60 km transmissions experimentally measured and measured by mathematical simulation are closely similar to each other. In mathematical simulation software, optical spectrum analyzer (OSA) uses extra signal processing function; therefore, at the noise level (~70 dB), the lines are smoother (less amount of noise) than in the experimental setup results. The obtained similar simulation and experimental results prove that the mathematical simulation model has been created correctly.

FBG sensor network with optimal parameters (developed and described in the article, see Figure 12) is then integrated into the developed and experimentally validated simulation model and tested after BTB, 20, 40, and 60 km long transmissions. As we can see in Figure 17, after 60 km transmission, it is possible to detect the received signals of FBGs central wavelengths, and side-lobe suppression ratio (SLSR) values are 9-11 dB. This means that the developed FBG sensors network can be used for long-distance (60+ km) monitoring solutions.

4. Conclusions

In this research, we have analyzed and defined optimal grating and apodization parameters that provide maximally high reflectivity (at least 90%) and acceptable SLS (at least 20 dB), and maximally narrow bandwidth (FWHM <0.2 nm) for FBG sensor networks and long-distance monitoring applications. In the article, we have estimated optimal FBG parameters for Gaussian apodization, sine apodization, and raised sine apodization when modulation indexes 1×10^{-4} , 1.5×10^{-4} , and 2×10^{-4} are used. From the apodizations used in this research, raised sine apodization was found to be the most optimal for the application in FBG sensor networks and long-distance (60+ km) monitoring if the binding parameters (as described in this work) are used.

Data Availability

The data generated in this study have been deposited in the open repository, Zenodo [15].

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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