

# Development of fiber Bragg gratings technology and their complex structures for sensing, telecommunications and microwave photonics applications

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**Abstract.** In this paper research on the development of the fiber Bragg grating (FBG) technology which has been conducted at the Institute of Electronic Systems (IES), Warsaw University of Technology (WUT) since 2004 is presented. In particular the directions in the development of advanced set-ups employing the phase mask inscription scheme are discussed and supported with the descriptions of structures designed and fabricated with the use of the laboratory stages constructed at the IES. The novelty of the presented solutions is based on the combination of numerous techniques of the external modification of the interferometric patterns (projected onto cores of photosensitive fibers to modulate their refractive index) as well as application of the modification of the internal properties of the waveguides themselves by the means of introducing strain or tapering.

The development of these sophisticated set-ups resulted in the inscription of FBGs with precisely designed spectral characteristics which found application in telecommunications and sensor technology are also illustrated here.

The paper is summarized with the specification of the most important achievements attained at the lab and drafting of the possible directions of further research.

**Key words:** fiber Bragg gratings, phase-shifted FBG, superstructured FBG, optical fiber tapers, fiber optic sensors, microwave photonics.

## 1. Introduction

Fiber Bragg Grating [1, 2] are in-waveguide components with a periodic modulation of the fiber core refractive index typically obtained with the irradiation by the pattern of interferometry fringes in the UV range. Their operation resembles well known in electronics band-stop filtering but in the optical domain with the resonant frequency corresponding to the so called Bragg wavelength [1, 2] which can be expressed with a simple equation:

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where  $\lambda_B$  is the Bragg wavelength,  $n_{eff}$  – the effective refractive index of the fiber core for the propagating mode and  $\Lambda$  is the grating period. Flexibility in the adjustment of the characteristics of the FBG based optical filters together with their capability to be sensitive for external conditions (most often temperature and strain as well as other phenomena affecting the refractive index of the mode-guiding fiber area) resulted in continual broadening of their applications mainly in telecommunication and sensors practically since 1978 when FBG was reported for the first time by Hill [3]. Besides of their properties, the factor which decided on the success of FBGs was development of the efficient and powerful inscription techniques. In contrary to the so-called internal method discovered by Hill, which relied on inducing a standing wave

in a fiber, the new external method [4] exploited the application of the interference pattern obtained by the separate interferometric set-up. It gave incomparably larger flexibility in adjustment of the Bragg wavelength and overall spectral characteristics. The subsequent milestone was the development of the phase mask [5, 6] – a diffractive component of the properties extremely convenient for the FBG inscription. Abundance of the set-ups based on diverse modifications offered by the phase mask fruited in numerous new types of FBGs as chirped [7–9], tilted (blazed) [10], phase shifted [11], superstructure [12], etc. with parameters precisely tailored for given applications.

The phase mask methods quickly have dominated over other techniques due to simplicity and flexibility of the application and great reproducibility of the inscribed gratings; however; also faced some limitations unavoidable for the developers. The most obvious one among them was the need of having a specific phase mask for a given grating structure with a fixed parameters of periodicity (Bragg wavelength, chirp, etc.). On the other hand, in the research progress numerous approaches emerged which facilitated relieving from this limitation. Some of them, especially those applied at the IES, will be described further in this paper.

The research on the FBGs at the Institute of Electronic Systems at the Warsaw University of technology started in

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2004 and the first achievements were the phase mask interferometric set-up for grating description with the flexibility in the wavelength domain [13] and the scanning phase mask set-up for inscription of long gratings with an adjusted apodization [14] profile for the first time presented in [15].

Further works were aimed at the increasing of the flexibility and introducing automation in the set-ups employing phase mask in both interferometric and scanning beam arrangements and on extending the applicability of the method from standard hydrogenated [16] fibers (i.e. which were especially prepared for the FBGs inscription) to other types of fiber optic waveguides and components as polarization maintaining fibers [17] and tapers [18].

The present paper is mainly focused on the description of sophisticated FBG structures with the use of various modifications of the phase mask set-up. In the subsequent sections there are presented the ideas which led to the set-up evolution, examples of the attained structures together with their applications and finally the summary with foreseen directions of the future developments.

## 2. Extending the possibilities of the phase mask FBG inscription at the IES

The mentioned in the introduction limitations of the basic phase mask set-up can be overcome by the means of two general approaches. The first one (I) employs modification of the interferometry fringe pattern which can be implemented by the means of the laser beam control together with (the most often) real-time adjustment of the mechanical and optical set-up constituents. The alternative one (II) employs the modification of the internal properties of the fiber which the grating is going to be inscribed on and, in general, it requires a controllable change in the waveguide geometry in the way that will be described later in this section.

When the approach (I) is under discussion one can identify four independent schemes allowing for the extending the method functionality:

1. Modification and control on the irradiation time, particularly during the beam scanning over the phase mask. This scheme can be easily employed by a simple motion stage equipped with a controllable step or linear motor. Such a straightforward improvement gives a full flexibility over the energy dose deposited onto a given length range of the fiber, thus enabling the control over the refractive index change due to the laser irradiation. It makes it possible to obtain arbitrary profiles of apodization which directly correspond to the spectral properties of the inscribed FBGs. Another method to get non-homogeneous (apodized) fringe pattern distribution along the grating length is to use a phase mask with variable diffraction efficiency [19–21].
2. Modification of the Bragg wavelength of the FBG with the use of the localized irradiation through a chirped phase mask [22]. This scheme is the easiest one among those which are aimed at adjustment of the Bragg wavelength.

However useful it is; its application is associated with “fundamental constraints” due to the parameters of the phase mask applied. Which is obvious even at the first glance – the Bragg wavelength of a grating inscribed in this way must be unavoidably in the wavelength range of the chirped grating (unless critical modifications to the set-up geometry are introduced but it corresponds to change to phase mask interferometer or tilted gratings set-up which significantly exceeds the scheme of direct phase mask grating inscription). The inscription of the grating in this scheme connects the FBG bandwidth and maximum reflection with the chirp of the phase mask. In general – if a grating is longer it has a narrower bandwidth and higher reflection, so e.g. if one needs a grating with higher reflection, then a longer grating is needed. On the other hand, one needs to carry in mind that the grating corresponds to the section of a chirped grating and a longer it is, the broader is the bandwidth. Nevertheless, there is another factor which can be adjusted to help obtaining given grating parameters – refractive index modulation corresponding to the irradiation energy dose controlled by the exposition time or output power of laser. As it can be seen in the discussion above – inscription of gratings with the use of this scheme may be quite complex and demanding a compromise solution, but still offers flexibility in the output parameter choice.

3. Modification of the periodicity of the interference pattern by introducing a precise discrete movement between the phase mask and the fiber being irradiated which results in the phase-shift of the interferometric fringes. Executed with a precise nano-positioner it can change the spectral characteristics in a very sophisticated way which manifests in formation of a very narrow passing peak inside the stop band. Gratings fabricated in this way are called phase-shifted FBGs.
4. Control of the irradiation region – by a straightforward control of a beam shutter with a simultaneous movement of the fiber in regard to the phase mask other sophisticated components can be obtained which are called superstructure FBGs and consist of a number of separate gratings with flexibly adjustable coupling coefficient. In the wavelength domain it results in formation of a comb-like structure in the reflection spectrum.

The alternative approach (II) deals rather with the waveguide itself than with the parameters of the inscription set-up; however; it still needs to be adapted for the installation of additional components. Basically, there are two types of possible modifications:

5. Introducing the strain to the fiber by the means of thermal or mechanical factors which directly affects the periodicity patterned on the waveguide. This feature gives a great flexibility of inscription of chirped gratings even with the use of standard uniform phase mask. Which is also important, a grating inscribed on a specially prepared [24] strained fiber has a broadened spectrum (due to the inherent chirp), but it narrows when it is strained to the value as was present during the writing process.

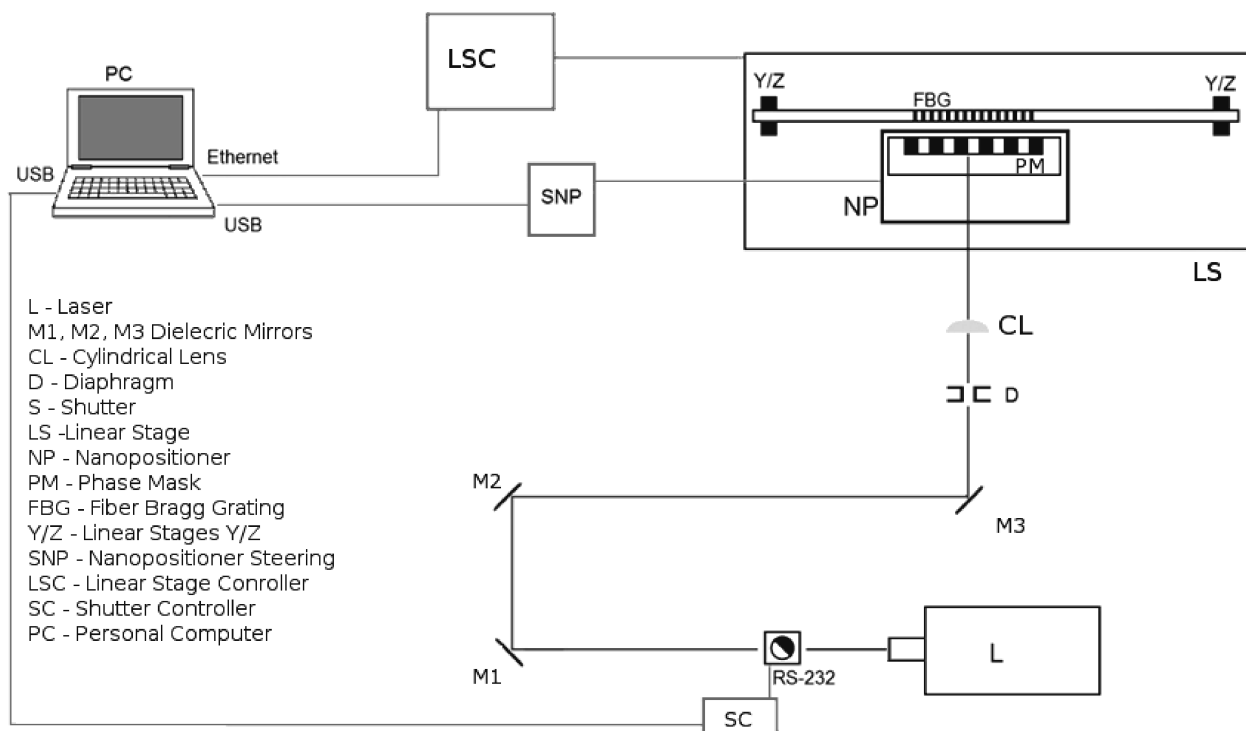


Fig. 1. The laboratory stage for versatile FBG inscription

6. Inscription of a uniform grating on a tapered fiber which leads to obtaining a structure with chirp resulted from the inherent properties of the tapers. To briefly describe this phenomenon it needs to be mentioned that the thermal tapering with the change of the geometric parameters of the fiber modifies also its effective refractive index [23]. Now it can be easily imagined that if the tapered fiber cross-section continuously changes it consequently changes the local value of the effective refraction coefficient which results in continuous modification of the local Bragg wavelength according to the equation (1) exactly as in a chirped FBG. It is also worth to stress that further advantages can be attained when the technique is combined with straining the fiber described in 5) [24].

The incorporation of the described modifications has led to design the versatile laboratory stage which is presented in Fig. 1.

In the set-up presented in Fig. 1 the modifications 1) and 2) are employed with the use of the linear motion stage (LS) and linear stage controller (LSC). The phase shifts described in 3) are obtainable with the use of the nanopositioner (NP) and nanopositioner steering (SNP). The beam deposition can be turned on or off with the shutter controller (SC) which introduces the modification described in 4). All the components are mounted on the optical table with attenuated vibration and controlled by the dedicated software installed on the PC.

The performance of the stage and the structures inscribed with it have been tested in a way described in the next subsection.

### 3. Validation results of the setup

**3.1. Phase-shifted and superstructured gratings.** As it was mentioned in the previous section, the modification of FBG fringe pattern can be obtained by changing the relative position between the phase mask and the optical fiber as well as by the irradiation process using beam shutter correlated with the scanning speed. In order to validate presented setup, especially accuracy and precision of the nanopositioning as well as the velocity of scanning (and thus the irradiation time at given sections), phase-shifted and superstructure FBGs were fabricated. Both structures were written on hydrogen-loaded optical fibers using uniform phase mask with 1061 nm pitch and frequency doubled CW argon ion laser (Coherent) with 100 mW output power.

The first structure was the phased shifted grating of a length of 10 mm and the phase shift incorporated precisely in the centre of the structure (at the 5<sup>th</sup> mm). The overall scanning time for the whole structure equalled 400 sec. In this way the feasibility of the incorporation of modifications 1) and 3) described in the previous subsection has been tested and confirmed. A theoretical relative displacement of phase mask, which results in introducing  $\pi$ -phase shift is a quarter of the phase mask period, which corresponds to the 265.25 nm. However, in practice, this value should be a bit corrected due to the fact, that the area of phase shift is also irradiated, and the local refractive index, (phase shift) is additionally increased. Thus the optimal phase shift introduced by the phase mask displacement was set to 250 nm. In Fig. 2a the spectral transmission characteristic of phase-shifted fiber Bragg grating is presented.

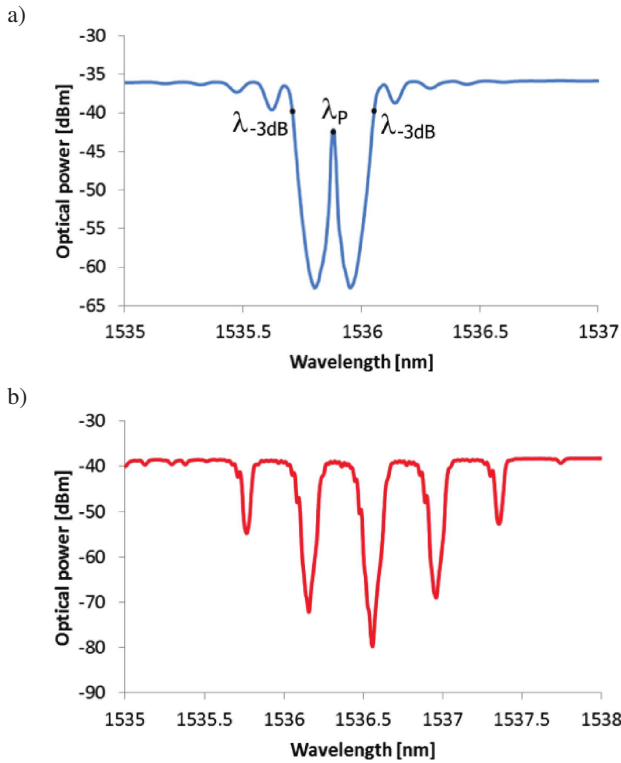


Fig. 2. Spectral transmission characteristics of phase-shifted a) and superstructured b) fiber Bragg gratings used for validation of inscription setup

As the criterion for the performance validation the symmetry in the grating spectral characteristics has been assumed. For this purpose, first the central wavelength ( $\lambda_{AV}$ ) has been calculated as the average value of the  $\lambda_{-3dB}$  wavelengths corresponding to the values for which the reflection coefficient equaled 50% and then  $\lambda_{AV}$  has been compared with the wavelength which corresponded to the center of the transmission peak ( $\lambda_P$ ). The verification brought satisfactory results which are tabulated in Table 1.

Table 1  
Parameters of the spectral response of inscribed phase-shifted fiber Bragg grating

-3 dB wavelengths	Average -3 dB wavelength	Peak wavelength
$\lambda_{-3dB}$ [nm]	$\lambda_{AV}$ [nm]	$\lambda_P$ [nm]
1535.707	1535.881	1535.881
1536.055		

To validate the performance of the set-up for the inscription of the superstructures a grating consisting of 12 FBG sections of 0.65 mm separated by 1.4 mm segments has been written in a fiber with the irradiation time for a single section of 40 sec. The transmission spectrum measured for this structure is shown in Fig. 2b. The feature which is characteristic for this type of structure is a constant spectral distance between the neighboring peaks which can be calculated by the following formula [25]:

$$\Delta\lambda = \frac{\lambda_B^2}{2n_{eff}P}, \quad (2)$$

where  $P$  is the microstructure period equals to the sum of the length of a section and the inter-section distance (here 2.05 mm). In this case the criterion for validation is the comparison of the distance between the peaks of the structure from Fig. 2b and one calculated with the Eq. (2). The wavelengths corresponding to subsequent peaks are tabulated in Table 2.

Table 2  
Parameters of the spectral response of inscribed superstructured fiber Bragg grating

Peak optical power [dBm]	Peak wavelength [nm]	Peak-peak wavelength difference [nm]
-54.8	1535.764	0.391
-72.2	1536.155	0.402
-79.8	1536.557	0.400
-69.0	1536.957	0.396
-52.8	1537.353	

The average peak-peak wavelength difference resulted from measured transmission spectrum (Fig. 2b) of superstructured grating is 0.397 nm and is very consistent with theoretical one 0.4 nm.

**3.2. Tapered FBG with custom spectral response.** The theory and technology of tapered fiber Bragg gratings for telecom and sensing applications have been under development at the IES for few years [26–28]. The combination of non-standard irradiation process and unique profile of tapered optical fibers gives great possibilities for shaping the spectral characteristics of such structures [29]. In this way, two 6 mm long uniform gratings separated by  $\sim 1$  mm were written into a tapered optical fiber. As the result, a structure with the narrow transmission dip in its spectral reflection characteristic was achieved (Fig. 3). The central wavelength of the transmission gap is 1533.81 nm and its spectral width is 30 pm. Finally, by combining the functionalities 1), 4) and 6) the spectral characteristic similar to those typical for phase-shifted grating is reached without any phase mask-optical fiber displacement with nanometer precision. Additionally, due to the variable  $n_{eff}$  in the tapered region, Bragg wavelengths corresponding to both grating sections are different and thus Fabry-Perot effect practically does not occur.

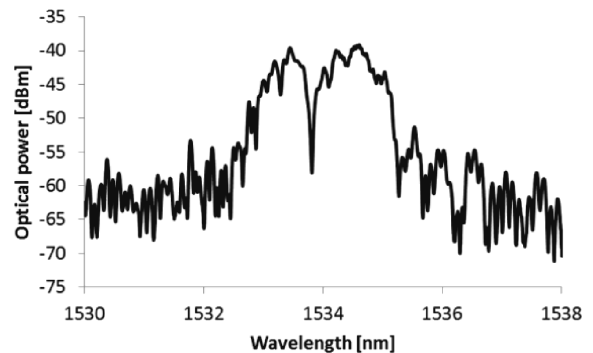


Fig. 3. Spectral reflection characteristic of complex tapered fiber Bragg grating with narrow transmission band



**3.3. Optimisation of fabrication of quasi-uniform fiber Bragg grating using chirped phase mask technique for microwave photonics applications.** As it was mentioned in Sec. 2; however the phase mask method is limited for the inscription of the gratings of the Bragg wavelength corresponding to the phase mask, if a chirped phase mask is available it is still possible to adjust the Bragg wavelength of an inscribed short grating (see the modification 2) in Sec. 2. In Fig. 4a results of modelling are shown for spectral transmission characteristics of the gratings of different lengths prepared by the means of a phase mask with the chirp of 0.35 nm/mm (which corresponds to the chirp of the spectral characteristics equal to 0.5 nm/mm). Accordingly in Fig. 4b the dependence of the grating spectral width (FWHM) on grating length is shown. The results indicate that the optimal grating length which ensures minimal obtainable spectral width was approximately 2 mm. A grating obtained in this way has properties close to the uniform one which explains why it is called a quasi-uniform fiber Bragg grating (QUFBG). For the longer structures a significant bandwidth broadening can be observed without an adequate increase in the reflection coefficient. On the other hand, for the gratings considerably shorter, the reflection coefficient becomes too low.

Figure 4c shows the reflection spectrum of the serial set-up of three quasi uniform FBGs of a lengths of 2 mm separated by 0.5 m each. This type of structure has found an application in the opto-electronic oscillators where it can operate as a phase shifter (Fig. 5a) in configuration shown in [30, 31]. The principle of operation is based on the discrete control of the group delay with the use of the adjustment of the TLS laser wavelength (TLS – Tunable Laser Source). The optical signal from the laser (which is modulated by the RF signal) is provided via circulator to the branch with the FBGs. In the dependence of the wavelength of the laser optical signal the wave is reflected from a given grating (FBG1, FBG2 or FBG3). In this way it experiences the group delay dependent on the wavelength which can be expressed by a formula:

$$\tau(\lambda) = 2kn_{ef}L/c_0, \quad (3)$$

where  $L$  is the distance between subsequent gratings,  $c_0$  velocity of the light in vacuum,  $k$  indicates the position of the grating which reflects the wave. The phase characteristics for the oscillator with three Bragg wavelengths is shown in Fig. 5b. Accordingly in Table 3 the values of group delays generated by FBG based phase shifter are presented.

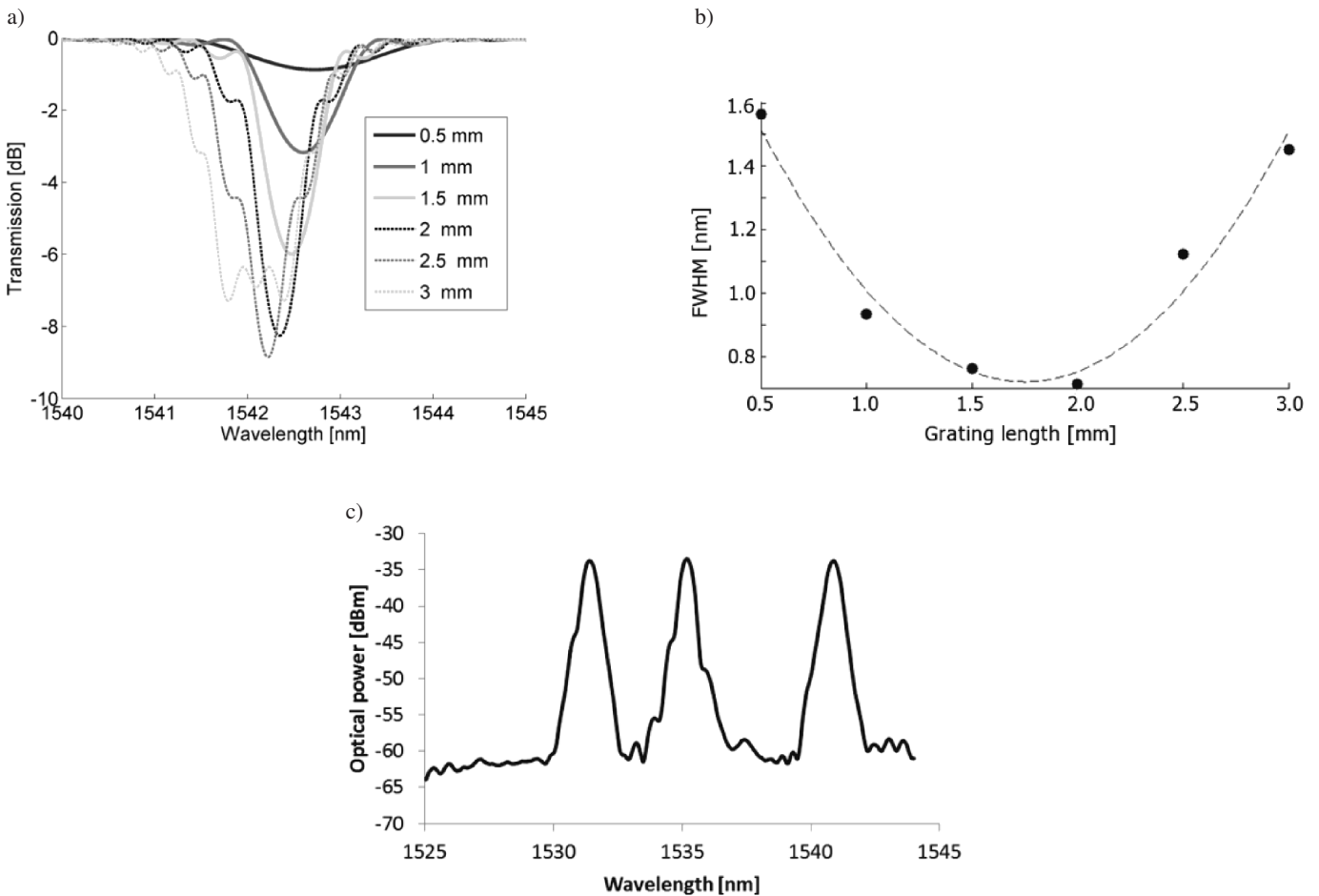


Fig. 4. Results of optimization and inscription of quasi-uniform FBG (QUFBG) using chirped phase mask method: a) QUFBG spectrum for various grating length, b) FWHM vs. grating length and c) measured spectrum of three QUFBG (FBG1, FBG2 and FBG3) separated by 0.5 m, inscribed in one section of the optical fiber

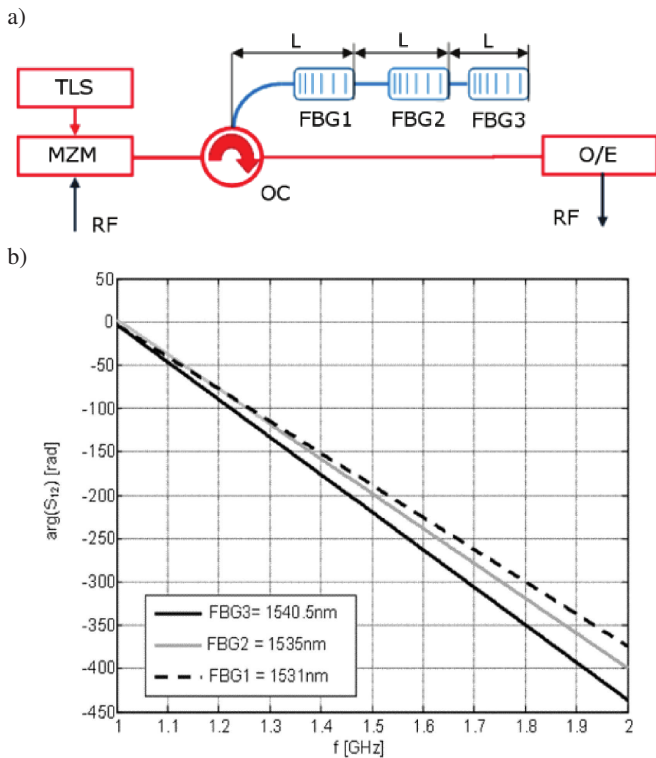


Fig. 5. FBG based phase shifter for opto-electronic-oscillator: a) scheme, b) phase characteristic of the open loop OEO with FBGs included. TLS – tunable laser source, MZM – Mach-Zehnder modulator, FBG1, FBG2, FBG3 – quasi uniform fiber Bragg gratings separated by  $L = 0.5$  m, O/E – opto-electronic converter (detector), OC – optical circulator

Table 3  
Group delay values generated by FBG based phase shifter

Grating label k	Central wavelength [nm]	Group delay [ns]
FBG1	1531.0	4.8
FBG2	1535.0	9.6
FBG3	1540.5	14.5

The second practical application of the QUFBGs can be a distributed sensor network in a configuration of a series of subsequent gratings of given Bragg wavelengths which are inscribed on a single fiber at given locations. In such networks parameters of the gratings obtained with the use of a single chirped phase mask are satisfactory and compatible with the standard interrogators commonly used in fiber sensor networks.

#### 4. Possible directions of the further progress

Besides of the works presented in this paper other research is in progress at the IES which is concerned on equally important issues as the development of the automated phase-mask interferometer stage (which is going to be a considerably extended version of the early works started with efforts described in [13]), application of the new pulse excimer laser for inscription of type II gratings and incorporation of polarization effects in the FBGs. Together with the further developments of

techniques presented in this paper, these research directions are expected to have a significant contribution in the further achievements of the team of the FBG laboratory at the IES.

It needs to be stressed here, that for the topical area presented in this paper, up till now, the main effort has been put for the development of the methods of inscription themselves. Now when, as it has been briefly presented here, the techniques are being very close to be optimized, it is time for the work on their adjustment for given application in the sensor and communication fields. Some concepts towards research in these directions have been already made up in the fields of on-line life function monitoring in the environments with heavy electromagnetic interference and in industrial installations applied in metallurgy and mining. Participating in large interdisciplinary programs aimed on the investigation in the fields as mentioned are going to be a great opportunity of gaining resources and collaborative advantages for the FBG laboratory team at the IES.

Another recent opportunity of extending the research and technological excellency of the team is in collaboration with the Institute of Plasma Physics and Laser Microfusion on the application of a femtosecond pulsed laser which can be used for the inscription of gratings with uncommon immunity for thermal loads. A successful research towards this direction can considerably enrich the possibilities of the FBG sensor for operation in harsh environments.

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