Interfacial Roughness and Temperature Dependence of Narrow Band Thin Film Filters for the DWDM Passive Optical Networks

Lubomir SCHOLTZ, Libor LADANYI, Jarmila MULLEROVA

Institute of Aurel Stodola, Faculty of Electrical Engineering, University of Zilina,
Kpt. Nalepku 1390, 031 01 Liptovsky Mikulas, Slovak Republic

scholtz@lm.uniza.sk, ladanyi@lm.uniza.sk, mullerova@lm.uniza.sk

DOI: 10.15598/aeee.v14i1.1576

Abstract. *In the design of new components for passive optical networks (PONs), the non-ideal properties are worth considering. In this paper the influence of interface roughness and temperature changes on final transmittance of downstream channels blocking filters for next generation dense wavelength division multiplexing passive optical networks(DWDM-PONs) is shown. The transmittance as the filter transfer characteristicswas calculated with the transfer matrix method. The roughness was expressed by root mean square deviations from an ideally smooth surface and was taken into account in the modified Fresnel coefficients. It is demonstrated how the interfacial roughness may increase the insertion loss and decrease the channel bandwidth which results in reduction of transmitted light energy through the filter.*

Keywords

DWDM, passive optical networks, PON, transfer matrix method, wavelength blocking filters.

1. Introduction

Currently considerable interest is given to future developments of passive optical networks (PONs) satisfying the demands for increasing traffic, higher bandwidth and extended reach [1], [2], [3]. The specific wavelength bands for present and future PON technologies are or should be allocated by recommendations of International Telecommunication Union (ITU). However, it is necessary to protect present and future PON signals in optical network units (ONUs) at the end of a subscriber from interference in case of coexisting PON technologies. To guarantee this, a precise scheme of the wavelength allocation together with the so-called guard bands and the implementation of specific wavelength blocking filters are generally accepted and recommended. Thin-film interference filters (TFFs) are suitable, low-cost, coexisting (i.e. ONU-independent) candidates [4], [5].

It is expected that the current gigabit-capable (G-PON) and 10 Gb·s^{-1} PON (XG-PON), the so-called next generation PON networks stage 1 (NG-PON1) will be followed by the NG-PON stage 2. As a primary solution for NG-PON2 TWDM (time wavelength division multiplexing) technology is planned. More candidates for NG-PON2 networks e.g. WDM (wavelength division multiplexing), OFDM (orthogonal frequency-division multiplexing) are possible, but TWDM is the most preferred. This also follows from the meeting of FSAN (Full Service Access Network) community in the April 2012 [6]. Since the TWDM-PON will be extended after several years of use it is necessary to study new possible options for improvement of these types of PON networks [7].

Just the use of TWDM technology is an evolutionary step to the future PONs. Because of the increasing demands for network capacity it is assumed that others wavelength pairs (resp. channels) will be added to existing PON infrastructure. Gradual increase of number of wavelength pairs should lead to the replacement of TWDM technology with pure WDM with dense division multiplexing. In WDM each subscriber has its own assigned wavelength pair. And thus signals are distributed through the optical distribution network (ODN) from the optical line terminal (OLT) to ONUs of all particular users separately. Dense wavelength division multiplexing passive optical networks (DWDM-PON) are considered as one of very promising technologies after NG-PON1 and NG-PON2 mass deployment. DWDM-PON may use the same ODN as GPON and NG-PON using colorless ONUs. However to secure coexistence between the various technologies it is necessary that subscriber's ONU will detect only the signals intended for this specific ONU. Therefore the unnecessary signals should be blocked. This can be ensured by using optical band filters in ONUs. This is a strong advantage for any new emerging technology from the cost saving point of view. Nowadays various groups deal with the concept of DWDM-PON searching for improvements [9], [10], [11]. For example in [9], [10] the modulation formats in DWDM-PON were examined since the use of modulation formats in access optical networks is the additional step to increase their capacities.

In our previous paper [8] narrow TFFs used at different angles of incidence are proposed to be used in future DWDM-PON to coexist with current PONs. The multilayer structures of filter were numerically designed with amorphous silicon (a-Si) as high refractive index material (H), SiO_2 as low refractive index material (L) and ZnO as middle refractive index material (M). The ZnO was used for the polarization independence of the filter. The polarization independence of the filter is important for our proposal of using the same filter in various ONUs in DWDM-PON where the filter is tuned by the angle of light incidence for the specific wavelength in a particular ONU. The setting of the specific angle of incidence is achieved by the filter rotation towards the normal. If in one subscriber's ONU the filter is set to the angle ϕ_x the filter is tuned to the channel x. In another subscriber's ONU the filter is set to the angle ϕ_y towards the normal what means that the filter is tuned to the channel y. Thus in DWDM-PON each ONU can be equipped with the same filter but in each of them at a different angle of incidence. This could be a strong advantage and cost-saving solution due to the fact that in ONUs for all subscribers only TFFs secure the selection of the right channel. This type of blocking filters can provide the coexistence with older PON technologies without replacing ONUs with new models.

The design presented in [8] presumes ideal smooth interfaces of the multilayer structure of filter. This paper deals with the influence of temperature and rough interfaces on the transmittance of narrow band pass TFF filters proposed in [8] for the following DWDM-PON downstream channels: channel A at the central wavelength 1540.5 nm ($\phi_A = 12.2$ °), channel B at the central wavelength 1521.7 nm ($\phi_B = 24.4$ °), channel C at the central wavelength 1502 nm ($\phi_C = 33.2$ °). These central wavelengths correspond to the Rec. ITU-T G.694.1 [12], with 100 GHz channel spacing. If the interface between two layers is not ideally smooth or the ambient temperature changes, the transfer characteristics of TFF filter may be negatively affected, what is the consequence of various undesirable effects.

2. Experimental

Transfer characteristics of multilayer filters can be calculated using the well-known transfer matrix method (TMM). The method expresses the relation between amplitudes of the forward E^+ and backward E^- electric field at the interface of the k-th and $(k-1)th$ layer of the structure depending on the parameters of layers and interfaces between layers. The phase change $\delta_{(k-1)}$ of light in the $(k-1)th$ layer depends on the thickness $d(k-1)$, on the complex refractive index $N(k-1)$ of $(k-1)th$ layer, on the wavelength of light λ and on the angle $\phi_{(k-1)}$ of incidence at $(k-1)th$ interface. It is well known that the complex refractive index N depends on λ and also on temperature T. This may be expressed as:

$$N(\lambda, T) = n(\lambda, T) + ik(\lambda, T), \quad (1)$$

where is the extinction coefficient expressing absorption of light in optical medium. Then the light transmission and reflection at the interface between k-th and $(k-1)th$ layer can be expressed in the matrix form as follows:

$$\begin{pmatrix} E^+_{(k-1)} \\ E^-_{(k-1)} \end{pmatrix} = \frac{1}{t_k} \begin{pmatrix} e^{i\delta_{(k-1)}} & r_k e^{i\delta_{(k-1)}} \\ r_k e^{-i\delta_{(k-1)}} & e^{-i\delta_{(k-1)}} \end{pmatrix} \begin{pmatrix} E^+_{(k)} \\ E^-_{(k)} \end{pmatrix}, \quad (2)$$

where r_k and t_k are the Fresnel coefficients representing the amplitude reflectance and transmittance of the k-th layer. Each interface is expressed with its own individual matrix. With these individual matrices, the final matrix and subsequently the total transmittance T and reflectance R for the whole structure can be computed. The total Tand Rarethen given by:

$$R = \frac{E^-_{(0)} E^{-*}_{(0)}}{E^+_{(0)} E^{+*}_{(0)}}, \quad (3)$$

$$T = \frac{N_{(m+1)}}{N_0} \frac{E^+_{(m+1)} E^{+*}_{(m+1)}}{E^+_{(0)} E^{+*}_{(0)}}, \quad (4)$$

where m is the total layer number, N_0 is the refractive index of the substrate, N_{m+1} is the refractive index of the ambient medium, usually air. E^+_0 (E^+_{m+1}) is the electric field amplitude of incident (outgoing) light, $E^-_{(0)}$ is the electric field amplitude of reflected light. The quantities denoted by a raised asterisk are complex conjugates of amplitudes of electric fields [13].

As the complex refractive index N is directly changed with the material density and the density normally varies inversely with temperature, it is not surprising that the refractive index varies inversely with temperature. Hence the change of temperature has influence on optical properties of a material. The change of the refractive index with temperature is defined by the thermo-optical coefficient $\frac{dN}{dT}$. The change of the refractive index resp. the extinction coefficient is different for each material.

If an interface which is not perfectly smooth occurs in the multilayer structure the final characteristics are obviously modified. Due to the scattering the wave propagations through rough and smooth interfaces differ. The resulting beam propagation or reflection is influenced by the random interface texture. Then the reflected and transmitted light power can be divided into two parts. The direct incident light is scattered into diffused components (diff) in reflection and in transmission, whereas the rest of light does not scatter, and is assigned to the specular components (spec). If the direct incident light is coherent, the specular component in reflection and in transmission has to preserve the coherence.

Intentionally created or modified roughness between two layers can by described by the modified amplitude Fresnel coefficients [13], [14], [15] as:

$$\begin{aligned} r_{k-1,k}^{(spec)} &= r_{k-1,k}^{(0)} e^{\left(-\left(\frac{2\pi Z N_{k-1}}{\lambda}\right)^2\right)}, \\ r_{k,k-1}^{(spec)} &= r_{k,k-1}^{(0)} e^{\left(-\left(\frac{2\pi Z N_{k}}{\lambda}\right)^2\right)}, \end{aligned} \tag{5}$$

where the superscripts (0) denote the Fresnel coefficients of smooth interfaces, Z is the root mean square (rms) roughness and N_k is the complex refractive index of k-th layer. The modified coefficients represent the phase differences in the reflected and transmitted beams and are based on the Gaussian distributions of the height irregularities. These coefficients are implemented into the specular part of directed light. The diffused part of light is easily calculable from equations [13], [14], [15]:

$$\begin{aligned} R^{(diff)} &= R^{(0)} - R^{(spec)}, \\ T^{(diff)} &= T^{(0)} - T^{(spec)}, \end{aligned} \tag{6}$$

where $R^{(0)}(T^{(0)})$ is total reflectance (transmittance) at a smooth interface, $R^{(spec)}(T^{(spec)})$ is specular reflectance (transmittance) at a rough interface.

Rms roughness Z is usually obtained from the AFM measurements and is given e.g. by the standard deviation of the values of surface heights of a measured sample area. Then Z is expressed by:

$$Z = \sqrt{\frac{\sum_{n=1}^{P}(z_n - \bar{z})^2}{P-1}}, \tag{7}$$

where $\bar{z}$ is the average of the surface heights within the given area, z_n is the current height value, and P is the number of data points within the given area. More definitions characterizing the surface roughness, for example the mean roughness or the peak-to-valley distances are commonly used, too [16].

These coefficients are included in the individual matrices. The relations for modified Fresnel coefficients are valid for the following conditions:

- The transmission and reflection are coherent.
- The planes (thin film layers) in structure are mutually parallel.
- The rms roughness of the roughness features is much smaller than wavelength of incidence light.
- The dimensions of illuminated parts of the boundaries are much larger than the wavelength of incidence light.
- The materials used in thin film multilayer structure are homogenous and isotropic from optical point of view.

As reported surface roughness of a thin film depends on deposition technology, surface roughness of the substrate, the film thickness, cleaning process, etc. and may reach several nanometers in case of the PECVD deposited a-Si layers [17]. For our simulations typical values of interfacial roughness of a-Si were used from [17], [18]. Therein a possible value of rms roughness of a Si layer of the thickness of 800 nm deposited on a thick substrate equals 5 nm.

3. Results and Discussion

The influence of rough interfaces and temperature changes was demonstrated upon TFF filter composed from 201 layers. The designed TFF structure is described by Eq. (8):

$$\begin{aligned} (HMLM)^{12} 4.375H (MLMH)^{13} \\ MLM(HMLM)^{12} 4.375H (MLMH)^{12}. \end{aligned} \tag{8}$$

The geometric thickness of the layers was set as follows: 145 nm for L-layer, 204 nm for M-layer and 160 nm for H-layer. The spacer H-layer is 4.375-times thicker than other H-layers. The values of all necessary refractive indices of the materials were taken from [19] and at the close vicinity of 1550 nm are for H-layer (a-Si) $N = 3.48$, for L-layer (SiO_2) $N = 1.44$, for M-layer (ZnO) $N = 1.92$. For substrate (fused silica) $N = 1.5$. We suppose that absorption in all materials involved is negligible, i.e. kis expected to be zero.

The filter structure was optimized to achieve as steep filter characteristics as possible and to keep the insertion loss of the filter less than -5 dB within the pass band. Maximum insertion loss -5 dB for downstream channels is required according to ITU-T Recommendation G.984.2 and also insertion loss outside the required pass-band width should be at least -32 dB [4]. These requirements we can observe in Fig. 1. In the figure ideal filterwhich has minimum insertion loss between cut-on and cut-off wavelengths and maximum possible insertion loss out of these wavelengths is shown (magenta). Required pass-band width at -32 dB as $\Delta\lambda_{32}$ and required pass-band width at -5 dB as $\Delta\lambda_5$ were set according to ITU-T Recommendation G.984 series corresponding to the power budget -32 dB for C+ grade of ODN [20]. The ratio of these parameters is the so-called abruptness coefficient. For an ideal band pass filter the abruptness coefficient is equal to one. On the other hand the filter contrast expresses how steep the edges of the filter are near the cut-off and cut-on wavelengths.

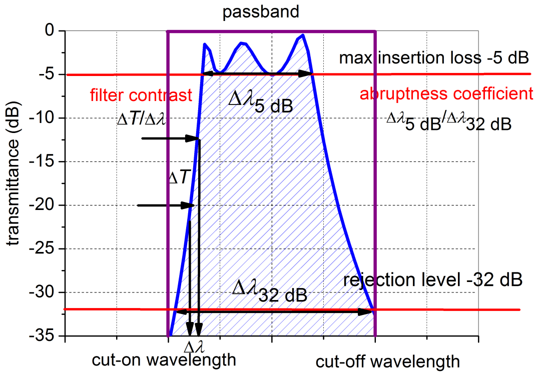

Fig. 1: Requirements for filter properties.

3.1. The Influence of Interface Roughness

It is known that the performance of a multilayer structure depends on optical properties of individual layers and their thicknesses. An ideal case predicts a homogeneous layer with ideally smooth and parallel interfaces. It is obvious to expect that any changes in surface and interface roughness of individual layers influence the performance of the whole structure.

If the roughness of substrate is not equal to zero in the production process, it is then distributed through the whole filter. This is due to subsequently depositing the filter layer by layer. In Fig. 2 the effect of interface roughness of the filter for channel A at the wavelength 1540.5 nm is depicted. If the interface roughness at each interface is equal to zero the filter has the minimal insertion loss which is approximately equal to -0.5 dB. The filter contrast is 96 dB·nm^{-1}. If the interface roughness at each interface is not equal to zero the insertion lossesare increased and the filter contrast is decreased. If rms is equal to 1 nm the filter contrast is decreased to 65 dB·nm^{-1} and insertion losses are increased to -2.5 dB. In case of rms roughnessof 2 nm the insertion losses are increased up to the value of -8 dB and the filter contrast is decreased to 43 dB·nm^{-1}. In this instance the insertion losses are higher as required by the ITU-T and its use is not appropriate. We conclude that filters with the values of rms roughness > 1 nm at each interface are not applicable.

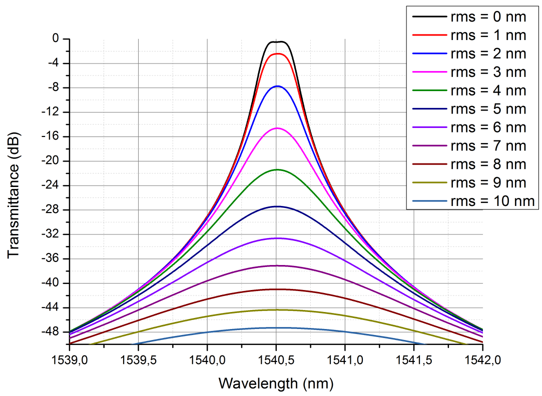

Fig. 2: Influence of interface roughness on TFF if roughness is applied at each interface. The case of channel at the wavelength 1540.5 nm.

Figure 3 shows the dependence of transmittance versus rms roughness. This figure was obtained from the simulations at the central wavelength of 1540.5 nm. From the figure it is clear that the transmittance decreases with increasing rms roughness in a nonlinear manner. The largest change in transmittance is seen for rms roughness from 1 nm to 6 nm. The filter with rms roughness of 6 nm has the transmittance smaller than -32 dB and thus the filter exceeds the power budget what means that does not meet the previously defined requirements.

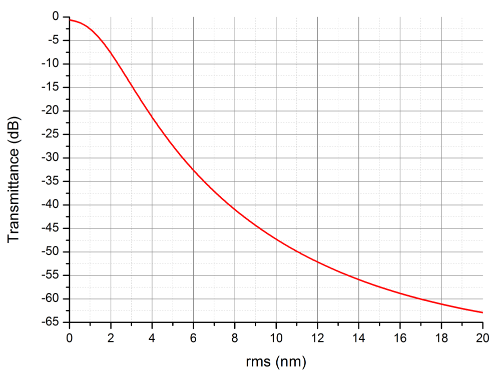

Fig. 3: Dependence of transmittance of filter on rms roughnessof the filter designed at the wavelength 1540.5 nm.

The objective of our further simulationsis to show that the sensitivity of particular interfacesto interface roughness differs. To prove this we change the value of roughness through the filter so that only at one interface the roughness is expected. The results are depicted in Fig. 4. From the figure it can be observed that the filter is minimum sensitive tothe interface roughness if it is applied at the filter boundary and at middle layers. On the contrary the highest sensitivityto the interface roughnesswas found at interfaces 48 and 152. These interfaces corespond to the interfaces between layers M and 4.375H. The layer 4.375H is the thickest in the structure of the filter what means that minimizing the interface roughness at this specific interface the decrease of the total transmittance of the filter can be minimized. Further we can see that at rms roughness of 5nm applied only at the 48th interface the total transmittance is decreased to value −4 dB however with rms equal to 10 nm at the same interface the total transmittance at 1540.5 nm is smaller than ∼10 dB. Due to this the higher roughness at the only one interface may also cause incompetence of the filter.

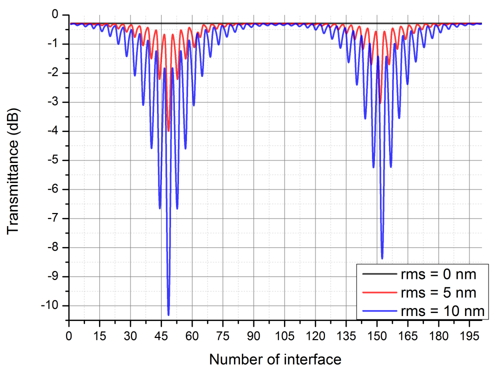

Fig. 4: Dependence of transmittance of filter to rms roughness for the wavelength 1540.5 nm in case if the rms roughness is gradually applied at only one interface.

Since the filter was designed for the application in DWDM-PON and the selection of the right channel is allowed by the rotation of the filter we must expect different impact of the roughness on the total transmittance for different rotations of the filter and in different wavelength regions. In the case the same rms roughness of 1 nm applied at each interface for the channel A at the central wavelength 1540.5 nm the increase of the insertion loss from −0.5 dB to approximately −2.5 dB can be seen (Fig. 5). However the same roughness at the same filter causes the insertion loss −2 dB for the channel C at the central wavelength 1502 nm. An even greater difference can be seen in the case of higher values of rms roughness. If rms roughness at each interface is equal to 3 nm the insertion losses are equal to −11.8 dB for channel C, −13.3 dB for channel Band −14.6 dB for channel A. Thus we conclude that for this

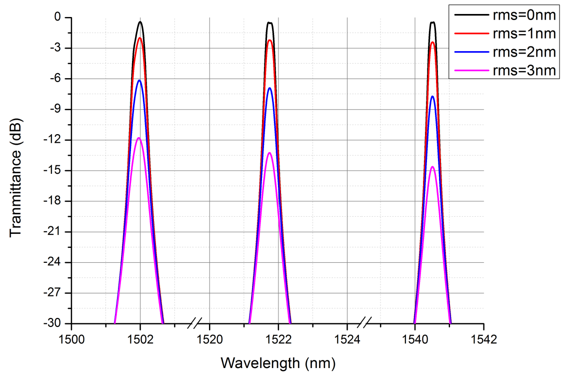

Fig. 5: Dependence of transmittance of filter on the rms roughness for the channels A at the central wavelength 1540.5 nm, B at the central wavelength 1521.7 nm and C at the central wavelength 1502.0 nm.

type of filter the roughness has the major impact on the filter designed for channels at higher wavelengths.

3.2. The Influence of Temperature Changes

Since ONUs may not be strictly set at the PON premises where the stable temperature is secured it is necessary to study the impact of temperature changes of ambient on the filter performance.

In this section we present the results of the simulations of this effect. The thermo-optical coefficients of the materials used for the simulations were taken from the references and are as follows:

- fused silica substrate $\frac{dN}{dT} = 0.0005{\cdot}10^{-4}\ \mathrm{K}^{-1}$,
- a-Si $\frac{dN}{dT} = 2.3000{\cdot}10^{-4}\ \mathrm{K}^{-1}$,
- SiO_2 $\frac{dN}{dT} = 0.1000{\cdot}10^{-4}\ \mathrm{K}^{-1}$ [21],
- ZnO $\frac{dN}{dT} = 0.3200{\cdot}10^{-4}\ \mathrm{K}^{-1}$ [22].

The results are illustrated in Fig. 6 where the transmittance of the channel A at 1540.5 nm is depicted. It can be seen that even if the temperature influence on the filter contrast factor and insertion losses are negligible the significant changes of the TFF central wavelength position are important. With the variations of temperature the central wavelength of the channel is changed. If the temperature drops from the room temperature 293.15 K up to 283.15 K the central wavelength is shifted so much that even the switching to the neighboring channel with the central wavelength of 1539.7 nm occurs. The switching to the completely different channel is highly undesirable. The same situation occurs at the temperature of 273.15 K. The temperature change of about 10 K causes the wavelength shift of 0.6 nm for this type of filter.

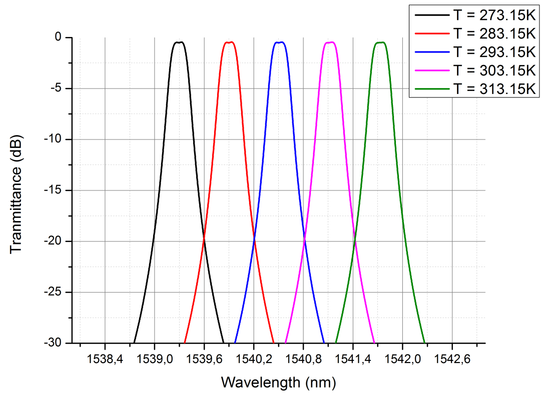

Fig. 6: Dependence of the transmittance of the filter on temperature changes for the channel A at the central wavelength 1540.5 nm.

The similar behaviour exhibits also the transmittance of the filter at the channel C as can be seen in Fig. 7. As in the previously mentioned case the temperature influences on the filter contrast factor and insertion losses are negligible but the wavelength shift of the filter transmittance spectrum at this channel is also equal to 0.6 nm. These numerical studies emphasize that the temperature protection is highly necessary for TFFs used in ONUs in this type of PONs.

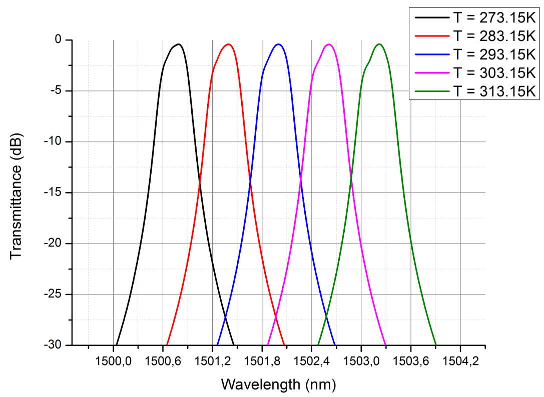

Fig. 7: Dependence of the transmittance of the filter ontemperature changes for the channel C at the central wavelength 1502.0 nm.

4. Conclusions

The numerical investigation of TFF filters designed for DWDM-PON definitely proved the negative effect of interfacial roughness on filter characteristics, especially the insertion loss and the filter bandwidth. It was shown that the impact of the interface roughness may differ according to the interface position and the spectral region and therefore must be studied very carefully. Moreover the influence of temperature of ambient on the transfer characteristics of filters was presented. It was shown that temperature changes result in wavelength shifts. These effects could be a drawback when using these filters as wavelength blocking filters in DWDM PONs. These effects must be anticipated via thorough simulations and suppressed during the deposition as much as possible. However, it should be added that the impact of interface roughness and temperature changes may be different for different structures of filter sand different materials used in the filter design.

Acknowledgment

This work was partly supported by the Slovak Research and Development Agency under the project APVV-0025-12 and partly by the Slovak Grant Agency under the project No. 2/0076/15.

References

[1] KANI, J. and K. SUZUKI. Standardization Trends of Next-generation 10 Gigabit-class Passive Optical Network Systems. *NTT Technical Review*. 2009, vol. 7, pp. 1–6. ISSN 1348-3447.

[2] ANDRADE, M. D., G. KRAMER, L. WOSINSKA, J. CHEN, S. SALLENT. and B. MUKHERJEE. Evaluating strategies for evolution of passive optical networks. *Communications Magazine* 2011, vol. 49, no. 7, pp. 176–184. ISSN 0163-6804. DOI: 10.1109/MCOM.2011.5936171.

[3] KORCEK, D. and J. MULLEROVA. Wavelength Protection within Coexistence of Current and Next-Generation PON Networks. In: *15th International Conference on Transparent Optical Networks (ICTON)*. Cartagena: IEEE, 2013, pp. 1–4. ISBN 978-1-4799-0682-6. DOI: 10.1109/ICTON.2013.6602980.

[4] UEHARA, A. N., R. OTOWA and R. OKUDA. Advanced Band Separation Thin-Film Filters for Coexistence-Type Colorless WDM-PON. In: *Optical Fiber Communication/National Fiber Optic Engineers Conference*. San Diego: IEEE, 2008, pp. 1–3. ISBN 978-1-55752-856-8. DOI: 10.1109/OFC.2008.4528711.

[5] MULLEROVA, J. and D. KORCEK. Superseparation thin film filtering for coexistence-type colorless WDM-PON networks. In: *13th International Conference on Transparent Optical*

Networks (ICTON). Graz: IEEE, 2011, pp. 1–4. ISBN 978-1-4577-0881-7. DOI: 10.1109/ICTON.2011.5970978.

[6] LUO, Y., X. ZHOU, F. EFFENBERGER, X. YAN, G. PENG, Y. QIAN and Y. MA. Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2). *Journal of Lightwave Technology*. 2013, vol. 31, iss. 4, pp. 587–593. ISSN 0733-8724. DOI: 10.1109/JLT.2012.2215841.

[7] SCHOLTZ, L., D. KORCEK, L. LADANYI and J. MULLEROVA. Tunable thin film filters for the next generation PON stage 2 (NG-PON2). In: *ELEKTRO*. Rajecke Teplice: IEEE, 2014, pp. 98–102. ISBN 978-1-4799-3720-2. DOI: 10.1109/ELEKTRO.2014.6847880.

[8] SCHOLTZ, L., D. KORCEK and J. MULLEROVA. Design of a Novel Wavelength Scheme for DWDM-PON Coexisting with Current PON Technologies and Protected Against Signal Interference. In: *16th International Conference on Transparent Optical Networks (ICTON)*. Graz: IEEE, 2014, pp. 1–4. ISBN 978-1-4799-5600-5. DOI: 10.1109/ICTON.2014.6876418.

[9] LATAL, J., J. VITASEK, P. KOUDELKA, P. SISKA, R. POBORIL, L. HAJEK, A. VANDERKA and V. VASINEK. Simulation of modulation formats for optical access network based on WDM-PON. In: *16th International Conference on Transparent Optical Networks (ICTON)*. Graz: IEEE, 2014, pp. 1–7. ISBN 978-1-4799-5600-5. DOI: 10.1109/ICTON.2014.6876473.

[10] CHOW, C. W. and C. H. YEH. Using Downstream DPSK and Upstream Wavelength-Shifted ASK for Rayleigh Backscattering Mitigation in TDM-PON to WDM-PON Migration Scheme. *Photonics Journal*. 2013, vol. 5, iss. 2, pp. 1–8. ISSN 1943-0655. DOI: 10.1109/JPHOT.2013.2247588.

[11] CHOVAN, J., F. UHEREK, R. KURINEC, A. SATKA, J. PAVLOV and D. SEYRINGER. Temperature characterization of passive optical components for WDM-PON FTTx. *Advances in Electrical and Electronic Engineering*. 2011, vol. 9, no. 3, pp. 143–149. ISSN 1336-1376. DOI: 10.15598/aeee.v9i3.512.

[12] ITU-T Recommendation G.694.1. Spectral grids for WDM applications: DWDM frequency grid. Geneva: ITU-T, 2012. Available at: `https://www.itu.int/rec/TREC-G.694.1/en`.

[13] SCHOLTZ, L., L. LADANYI and J. MULLEROVA. Influence of Surface Roughness on Optical Characteristics of Multilayer Solar Cells. *Advances in Electrical and Electronic Engineering*. 2014, vol. 12, no. 6, pp. 631–638. ISSN 1336-1376. DOI: 10.15598/aeee.v12i6.1078.

[14] DOMINE, D., F.-J. HAUG, C. BATTAGLIA and C. BALLIF. Modeling of light scattering from micro- and nanotextured surfaces. *Journal of Applied Physics*. 2010, vol. 107, iss. 4, pp. 044504-044504-8. ISSN 0021-8979. DOI: 10.1063/1.3295902.

[15] ZEMAN, M., R. A. C. M. M. VAN SWAAIJ, J. W. METSELAAR and R. E. I. SCHROPP. Optical modeling of a-Si: H solar cells with rough interfaces. *Journal of Applied Physics*. 2000, vol. 88, iss. 11, pp. 6436–6443. ISSN 0021-8979. DOI: 10.1063/1.1324690.

[16] FRIEDMAN, D. J. Progress and challenges for next-generation high-efficiency multijunction solar cells. *Current Opinion in Solid State and Materials Science*. 2010, vol. 14, iss. 6, pp. 131–138. ISSN 1359-0286. DOI: 10.1016/j.cossms.2010.07.001.

[17] PODRAZA, N. J., C. R. WRONSKI and R. W. COLLINS. Model for the amorphous roughening transition in amorphous semiconductor deposition. *Journal of Non-Crystalline Solids*. 2006, vol. 352, iss. 9–20, pp. 950–954. ISSN 0022-3093. DOI: 10.1016/j.jnoncrysol.2005.12.013.

[18] NASRULLAH, J., G. L. TYLER and Y. NISHI. An Atomic Force Microscope Study of Surface Roughness of Thin Silicon Films Deposited on SiO_2. *IEEE Transactions on Nanotechnology*. 2005, vol. 4, iss. 3, pp. 303–311. ISSN 1536-125X DOI: 10.1109/TNANO.2005.847007.

[19] PALIK, E. *Handbook of Optical Constants of Solids*. 1st ed. Cambridge: Academic Press, 1998. ISBN: 978-0-12-544415-6.

[20] ITU-T Recommendation G.984.2. Gigabitcapable passive optical networks (GPON): Physical Media Dependent (PMD) layer specification. Geneva: ITU-T, 2003. Available at: `https://www.itu.int/rec/TREC-G.984.2/en`.

[21] SCHOLTZ, L., D. KORCEK, L. LADANYI and J. MULLEROVA. Temperature dependence of TWDM narrow band thin film filters for the Next generation PON stage 2 (NG-PON2). In: *Applied physics of condensed matter*. Strbske Pleso: APCOM, 2014, pp. 232–235. ISBN 978-80-227-4179-8.

[22] JOHNSON, J. C., H. YAN, P. YANG and R. J. SAYKALLY. Optical Cavity Effects in ZnO Nanowire Lasers and Waveguides. *Journal of Physical Chemistry B*. 2003, vol. 107,

iss. 34, pp. 8816–8828. ISSN 1520-6106. DOI: 10.1021/jp034482n.

About Authors

Lubomir SCHOLTZ received his M.Sc. from the Department of Telecommunications and Multimedia, the Faculty of Electrical Engineering, the University of Zilina in 2013. His research interests include optical communication networks and systems and thin film filters for passive optical networks.

Libor LADANYI received his M.Sc. in 2011 and his Ph.D. in telecommunications in 2014 both from the Department of Telecommunications and Multimedia, the Faculty of Electrical Engineering, the University of Zilina. His research interests include optical communication networks and systems.

Jarmila MULLEROVA received her M.Sc. degree in experimental physics in 1980 and her Ph.D. in quantum electronics in 1988, both from the Comenius University, Bratislava. Since 2003 she has been with the University of Zilina. Since 2014 she has been a professor in the field of electro-technology and materials. Her ongoing research interests comprise optical properties of solids and thin films optics.