Design and Optimization of High-Channel Si_3N_4 Based AWGs for Medical Applications

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Abstract: We present the design and optimization of 80-channel, 50-GHz Si_3N_4 based AWG. The AWG was designed for TM-polarized light with a central wavelength of 850 nm. The simulations showed that, while the standard channel count AWGs (up to 40) feature gut optical properties and are relatively easy to design, increasing the channel counts (> 40 channels) leads to a rapid increase in the AWG size and this, in turn causes the deterioration of optical performance like higher insertion loss and, in particular, higher channel crosstalk. Optimizing the design we are able to design 80-channel, 50-GHz AWG with satisfying optical properties.

1 INTRODUCTION

Arrayed Waveguide Gratings (AWGs) are considered an attractive Dense Wavelength Division Multiplexing (DWDM) solution because they represent a compact means of offering higher channel count technology, have good performance characteristics, and can be more cost-effective per channel than other methods (Kaneko, 2002). However, their performance characteristics depend largely on the optical properties of the waveguide materials used. In terms of material, they can all be divided into two main groups, so-called low-index and high-index contrast AWGs.

Low-index contrast AWGs (Silica-on-Silicon (SoS) based waveguide devices) use SiO_2-buried rectangular waveguides, usually with a cross-section of ~ (6x6) μm^2 and a low refractive index contrast between the core (waveguide) and the cladding of Δn ~ 0.75%. They feature many advantages such as low fiber coupling losses in the order of 0.1 dB and low propagation loss (Leijtens, 2006). However, the low refractive index contrast means the bending radius of the waveguides needs to be very large, which leads to a rapid increase in the AWG size of several square centimeters that limits the integration density of SiO_2-based photonic devices.

High-index contrast AWGs, such as Silicon-On-Insulator (SOI) based waveguide devices, use a high refractive index difference $\Delta n \sim 58\%$. This is approximately one hundred times higher than that of typical SoS waveguides. Due to the fact that a waveguide size decreases proportionally to the increase in refractive index contrast, the waveguide size for this material composition shrinks into the sub-micron scale. Such high-index contrast makes it possible to guide light in waveguides with a far smaller bending radius, which leads to a significant reduction in the AWG size by more than two orders of magnitude when compared to SoS based AWGs (Pavesi, 2004). Such compact devices can easily be implemented on-chip and have already found applications in WDM systems as well as in emerging applications such as optical sensors, devices for biosensing and optical spectrometers for infrared spectroscopy (Bradshaw, 2005). The main problem arising from the reduced size of waveguides is the coupling of light from the fiber into such small waveguides, which causes much higher coupling losses, in the order of 10 dB, than in silica AWGs. The second drawback is the sensitivity of the mode index to the dimensional fluctuations (e.g. roughness) of the waveguide, which leads to a rapid increase in random phase-errors in the fabricated array grating

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arms (Lee, 2000). These technological imperfections affect the AWG performance by causing a marked increase in the channel crosstalk. In order to reduce the roughness of the waveguide sidewalls the high index contrast AWGs require very high-resolution fabrication technology that still presents a considerable challenge today.

An alternative to high-index contrast and low-index contrast AWGs is the Si_3N_4 material platform, which has a moderate index contrast lying between both main groups (Martens, 2015).

The goal of the silicon nitride waveguide based AWG development reported in this paper is to take a significant step towards the integration of spectral domain optical coherence tomography (SD-OCT) system operating in a wavelength range of 800 nm to 900 nm and having 0.1 nm resolution. OCT is a contact-free imaging method, which has become significantly important in ophthalmology to visualize the retina. In the course of the project, key-components of an SD-OCT system will be integrated on a single optical waveguide chip employing CMOS compatible processes.

2 AWG PRINCIPLE

Based on the substrate, an AWG consists of an array of waveguides (also called phased array, PA) and two star couplers (Fig. 1). One of the input waveguides launches the light consisting of multiple wavelengths λ_1-λ_n into the input star coupler, which then distributes the light amongst an array of waveguides. The light subsequently propagates through the waveguides to the output coupler. The length of these waveguides is chosen such that the optical path length difference between adjacent waveguides *dL* equals an integer multiple of the central wavelength λ_c of the demultiplexer. For this wavelength, the fields in the individual arrayed waveguides will arrive at the input of the output coupler with equal phase, and the field distribution at the output of the input coupler will be reproduced at the input of the output coupler. In the output star coupler the light beams interfere constructively and converge at one single focal point on the focal line in the image plane. In this way, for the central wavelength λ_c the input field at the object plane of the input star coupler is transferred to the center of the image plane of the output star coupler. If the wavelength is shifted to $\lambda_c \pm \Delta\lambda$ (i.e. λ_1, λ_2,..), there will be a phase change in the individual PA waveguides that increases linearly from the lower to the upper channel. As a result, the phase front at the input aperture of the output star coupler will be slightly tilted, causing the beam to be focused on a different position in the image plane. The positioning of the output waveguides at the focal points in the image plane allows the spatial separation of the different wavelengths (Smit, 1996).

3 AWG DESIGN

AWG design begins with the calculation of its dimensions, which are essential to create the AWG layout. The dimensions are given by the geometrical parameters, as shown in Fig. 1 (Seyringer[1], 2016):

1. minimum waveguide separation between PA waveguides (parameter *dd*),
2. minimum waveguide separation between input/output waveguides (parameter *dx*),
3. length of the star coupler (parameter *Lf*), and
4. optical path length difference between adjacent waveguides in the phased array (parameter *dL*).

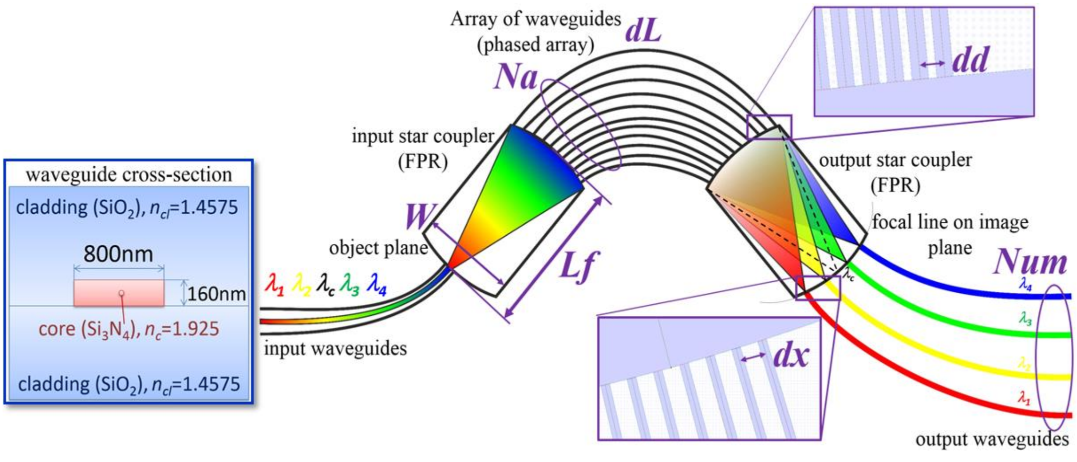

Figure1: Principle of an AWG with its design parameters and used waveguide cross-section.

Width of the coupler *W* is not a dominant parameter and can be freely changed. In order to minimize the loss of light capture in the arrayed waveguides, the number of arrayed waveguides *Na* should be sufficiently large. *Num* is a number of output waveguides (transmitting channels) that the AWG is designed for.

There are a couple of commercial photonics tools, available on the market that can be used to design and simulate AWGs. Particularly: WDM PHASAR from Optiwave, APSS Suite from Apollo Photonics, RSoft tool or Photon Design tool. For our AWG designs, we used WDM PHASAR, APSS Suite and RSoft tool. All AWGs were designed for the TM-like mode with a central wavelength of λ_c = 850 nm.

3.1 AWG-Parameters Tool

As the commercial photonic tools do not support (or only partially support) the calculation of the AWG geometrical parameters, we developed a new software tool called "AWG-Parameters" (Seyringer, 2013). This tool significantly reduces the time needed for AWG design and also facilitates an understanding of the relationship between input design and geometrical parameters. The calculations of this tool are based on the model of Smit and van Dam (Smit, 1996). The tool was used in many low-index contrast AWG designs and technologically well proven (Seyringer[1], 2016). Therefore, we used this tool to design Si_3N_4 based AWGs, too.

Figure 2 shows the user interface of this tool, presenting the design of Si_3N_4 based 8-channel, 100-GHz AWG. The input parameters for the calculation of AWG geometrical parameters are:

Technological parameters used to design waveguide structure ("Material" window in Fig. 2):

- Waveguide structure: width w = 0.8 µm (see also in Fig. 1 "waveguide cross-section").
- Effective index of the TM-like mode, $n_{eff,TM}$ = 1.50912,
- n_{out} is a refractive index of the cladding (n_{cl}) = 1.4575 (in Fig. 1 "waveguide cross-section").

AWG type parameters ("Transmission Parameters ←→ AWG Parameters" window in Fig. 2):

- Number of transmitting channels (output waveguides): *Num* = 8 (see also in Fig. 1).
- AWG central wavelength (λ_c): *Lambda* (µm) = 0.85.
- Channel spacing: *df* (GHz) = 100.

Transmission parameters ("Transmission Parameters ←→ AWG Parameters" window in Fig. 2):

- Adjacent channel crosstalk between output waveguides: *Cr* (dB) = -115.45.
- Adjacent channel crosstalk between arrayed waveguides: *CRaW* (dB) = -20.7.
- Uniformity over all output channels (also called non-uniformity): *Lu* (dB) = 1.

When the "Calculate" button is pressed, the tool calculates all necessary geometrical parameters given in Fig. 1 and displays them in the "Transmission Parameters ←→ AWG Parameters" window (Fig. 2):

- Number of arrayed waveguides: *Na* = 51 (see also in Fig. 1).
- Minimum waveguide separation between I/O waveguides: *dx* (µm) = 4.000967.
- Minimum waveguide separation between PA waveguides: *dd* (µm) = 1.200540.
- Coupler length: *Lf* (µm) = 181.927341.
- PA waveguide length difference: *dL* (µm) = 93.185026.

Figure 3 shows the spectral responses of this AWG simulated with all three photonics tools together with the measured characteristics of the fabricated AWG (applying the special taper structures, the fibre coupling efficiency for the used waveguide structure is in the range of 1 dB - 1.5 dB).

Minimum Waveguide Separation Between PA Waveguides (*dd*): One of the most important AWG performance parameters is insertion loss. This loss occurs due to reflection of the light at the facets of interspaces between the individual PA waveguides. Light penetrating the cladding material at these facets is usually absorbed. This loss can be minimized by maintaining only a small distance between the array waveguides (parameter *dd*) or by adding linear tapers; hence has to be considered already in the AWG design. Therefore, in the first designs (8-channel, 100-GHz AWGs) we studied the influence of the *dd* parameter on AWG performance, mainly on the losses. We varied this parameter from 1 µm to 1.2 µm, 2 µm and 2.5 µm applying AWG-Parameters tool. The design parameter *dx* was kept sufficiently large, *dx* = 4 µm (Fig. 2 shows one of these designs). Parameters *dL* and *Lf* were accordingly calculated. From all simulations was evident that decreasing the minimum waveguide separation between PA waveguides led to a strong reduction of the insertion loss, *IL* by about 4 dB. In comparison, the linear tapers, applied in PA waveguides, reduced losses by less than 1 dB (Seyringer[2], 2016).

Based on this study and considering waveguide width, w = 0.8 µm together with the fabrication limitations we fixed this parameter to *dd* = 1.2 µm.

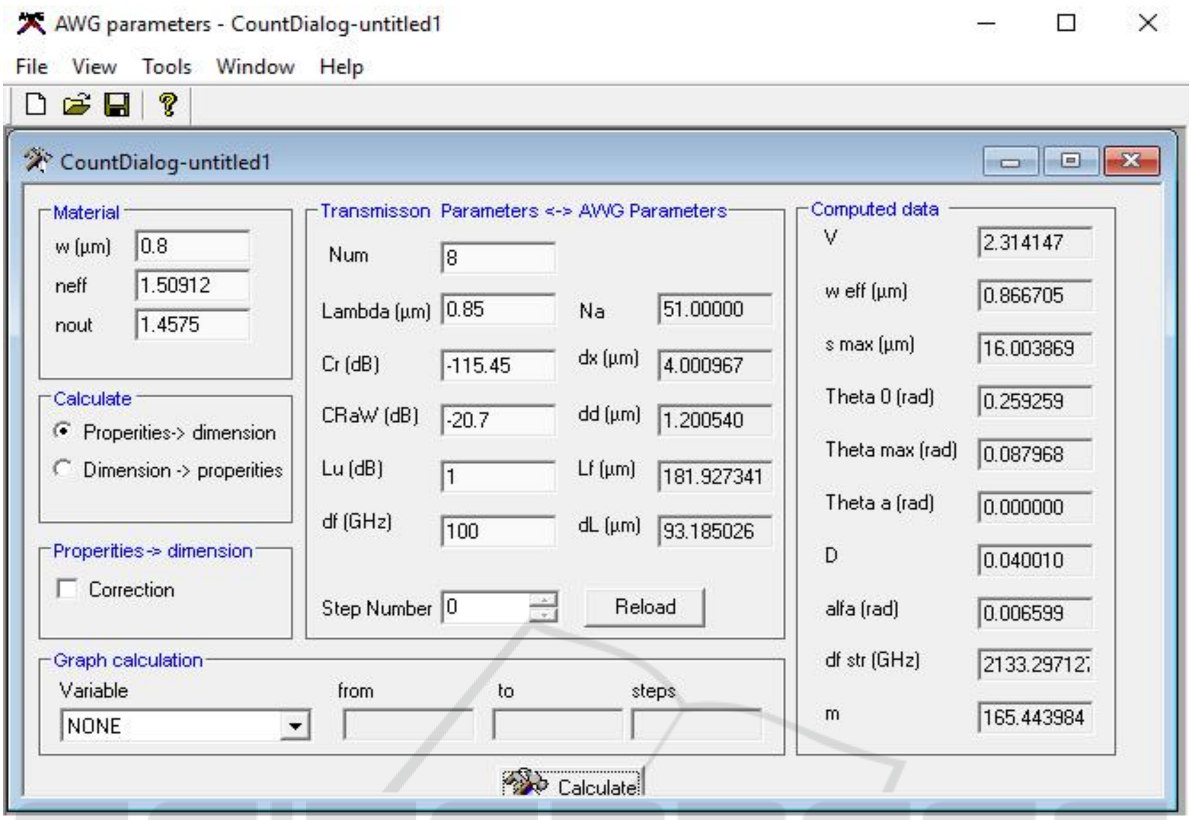

Figure 2: User interface of the AWG-Parameters tool presenting design of 8-channel, 100-GHz AWG.

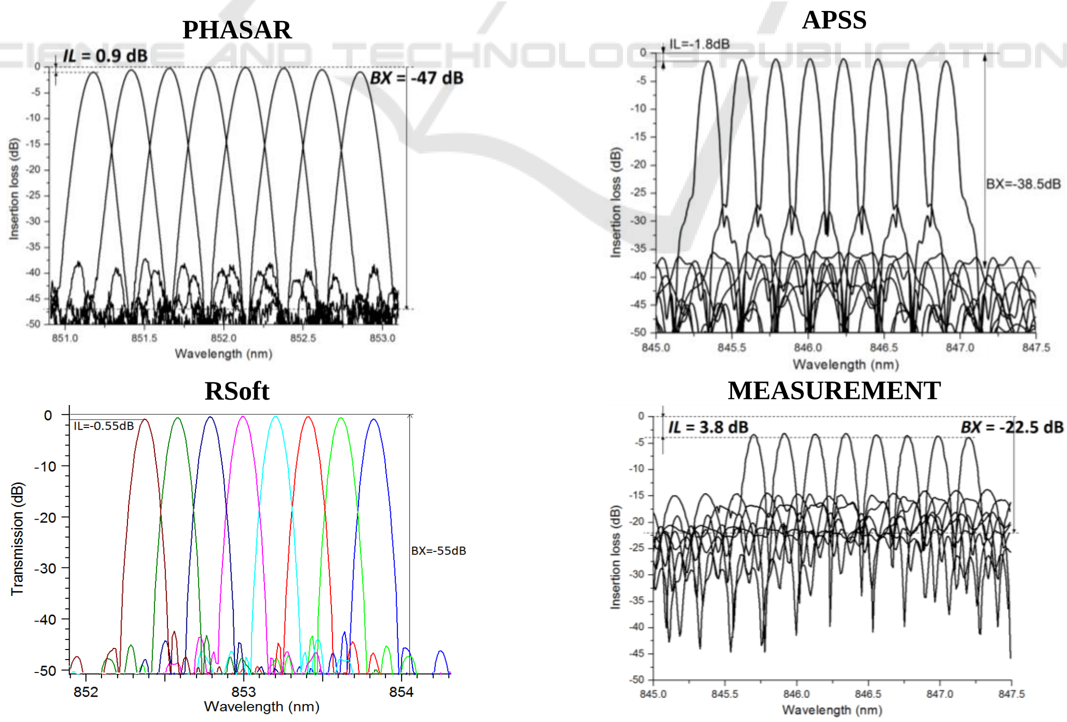

Figure 3: Simulated spectral responses of 8-channel, 100-GHz AWG from 3 photonics tools together with the measured characteristics from the fabricated AWG.

Minimum Waveguide Separation Between Input/Output Waveguides (*dx*): In the second step, it was necessary to fix the design parameter *dx*, i.e. minimum waveguide separation between input/ output waveguides. This parameter has an impact on the crosstalk between adjacent output channels. To this purpose, four 20-channel, 50-GHz AWGs with different output waveguide separations were designed with AWG-Parameters tool: *dx* = 2.5 µm, 3 µm, 3.5 µm and 4 µm and simulated applying all three photonics tools (Seyringer, 2017). The simulations showed that there is some minimum waveguide separation *dx* necessary to keep the crosstalk between output channels sufficiently low (in our AWG design, *dx* = 3.5 µm). At this separation, the output waveguides are positioned far enough from each other, to prevent the focusing of the power from selected channel into the neighbour output waveguides and vice versa. This implies that by increasing this value the performance of AWG did not change much (case of *dx* = 4 µm). If the waveguide separation was too small, the crosstalk strongly increased. This is in particular the case of waveguide separation *dx* = 2.5 µm and partially *dx* = 3 µm, where the AWG spectral response contained side-lobes inducing high channel crosstalk. Based on this study we fixed this parameter to *dx* = 3.5 µm.

We would like to point out that all above described designs were technologically verified and confirm the simulated results.

3.2 Design of 40-Channel, 50-GHz AWG

Based on the previous study we designed 40-channel, 50-GHz AWG. The AWG structure was then simulated applying WDM PHASAR tool and the spectral response is shown in Fig. 4. As can be seen, the transmitted optical signals are well separated from each other which is confirmed by low background crosstalk, *BX* = -42 dB (Fig. 4a). Adjacent channel crosstalk reached its highest value at the side-lobes in the middle of the spectrum, *AX* = 23.8 dB (Fig. 4b). In addition, the losses are very low (Fig. 4c). There are nearly no losses in the middle of the characteristics (the highest peaks) and there is about 1.2 dB loss at the lowest peaks (insertion loss, *IL*). This loss is mainly a result of the non-uniformity i.e. difference between the highest- and the lowest peaks; also called insertion loss uniformity, *ILu* = 1.18 dB (in AWG-Parameters tool labelled as *Lu* parameter). From this can be concluded that applying an optimized design based on the previous study of the design parameters in order to eliminate losses and crosstalk, the insertion loss was suppressed nearly to zero and the channel crosstalk is low, too.

4 DESIGN OF HIGH-CHANNEL AWGS

Above described optimized design ensures rather satisfying optical properties of AWGs up to 40 channels. However, the optical spectrometers for medical applications require much higher AWG channel counts. We will show that increasing the number of output channels (parameter *Num*) brings some additional design problems to be solved.

4.1 Design of 80-Channel, 50-GHz AWG

To this purpose, we designed 80-channel, 50-GHz AWG in which we used the same design parameters, i.e. *dd* = 1.2 µm, *dx* = 3.5 µm; and the parameters *Lf* and *dL* were calculated accordingly (we will call it DESIGN1). The AWG structure was then simulated applying WDM PHASAR tool keeping the same calculation conditions. The simulated spectral response is shown in Fig. 5. From the characteristics is evident that the optical signals are much wider compared to 40-channel, 50-GHz AWG (defined through the bandwidth, *B@5dB*, and *B@20dB*, i.e. a width of optical signal, measured at a −5 dB, and −20 dB drop from transmission peak), as can be seen in Figs. 4b and 5b. It causes the increase of insertion loss by nearly 1 dB (*IL* = 2.18 dB in Fig. 5c) and particularly much higher adjacent channel crosstalk, *AX* = 11.8 dB (Fig. 5b). Non-uniformity *ILu* is similar in both cases, since both AWGs were designed to have insertion loss uniformity about 1 dB. Background crosstalk, *BX* increased from -42 dB (40-channel AWG) to -38 dB (80-channel AWG, Fig. 5a).

4.2 Optimization of 80-Channel, 50-GHz AWG Design

Since the same design procedure as well as the same simulation conditions were used in both designs the question is what is the reason for such widening of the optical signals causing deterioration of the optical properties of designed 80-channel, 50-GHz AWG and how can be this negative effect eliminated.

We have tested various AWG design parameters and the deep study of the results showed that the reason for widening of the optical signals is the crosstalk caused by the coupling between PA waveguides.

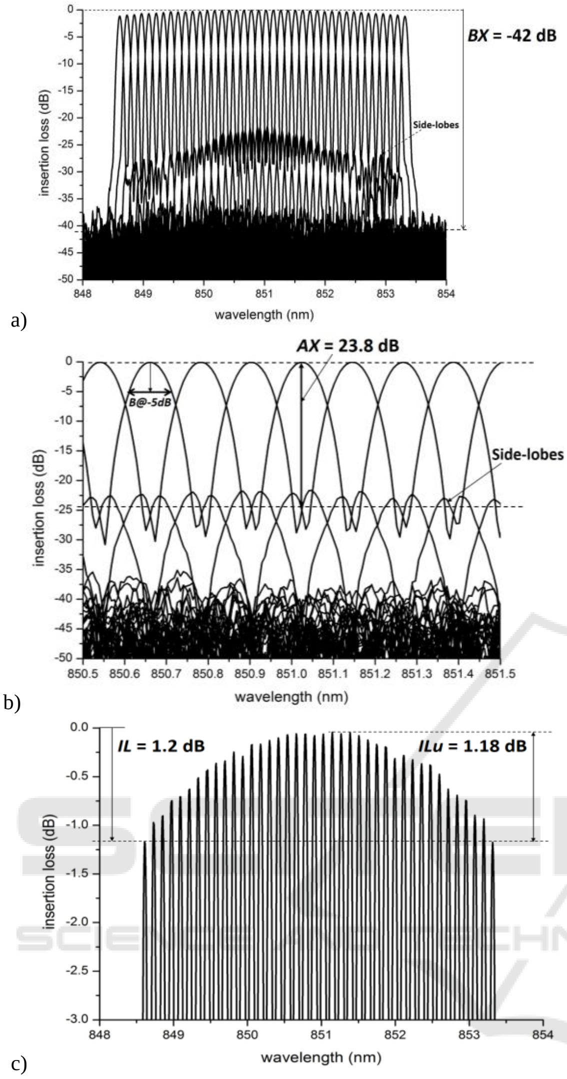

Figure 4: a) Simulated spectral response of 40-ch, 50-GHz Si_3N_4 AWG; b) detailed view of adjacent channel crosstalk, *AX* in the middle of the spectrum, c) detailed view of insertion loss, *IL* and insertion loss uniformity, *ILu*.

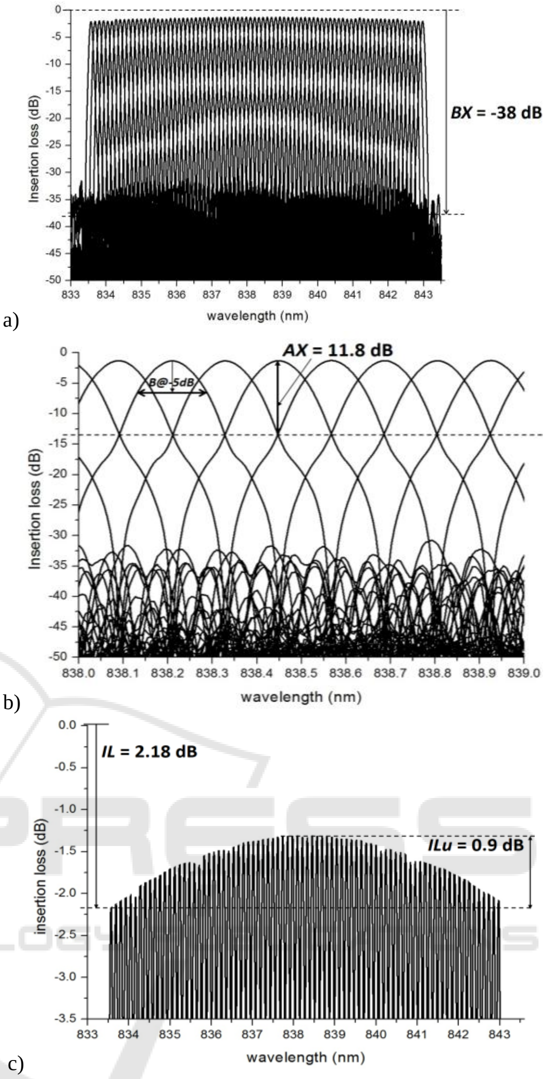

Figure 5: DESIGN1 - a) Simulated spectral response of 80-ch, 50-GHz Si_3N_4 AWG; b) detailed view of adjacent channel crosstalk, *AX* in the middle of the spectrum, c) detailed view of insertion loss, *IL* and insertion loss uniformity, *ILu*.

With increasing the number of output waveguides (parameter *Num*) the number of waveguides in the phased array (parameter *Na*) also increases and the optical path length difference between waveguides decreases. Therefore, the PA waveguides are placed much closer to each other. From this follows that the crosstalk caused by coupling in the PA can be avoided by increasing the separation between arrayed waveguides (Smit, 1996).

To show this influence we have designed the same 80-channel, 50-GHz AWG but with a different parameters, *dd* = 1.75 µm (DESIGN2) and *dd* = 2.2 µm (DESIGN3) keeping the parameter *dx* = 3.5 µm.

Figure 6 and Figure 7 show the simulated spectral responses of both AWG designs.

From the simulations is evident that the shape of optical signals is similar to the signal shape presented in Fig. 4 (40-channel, 50-GHz AWG). It ensures sufficient separation of the signals leading to the improvement of AWG optical properties.

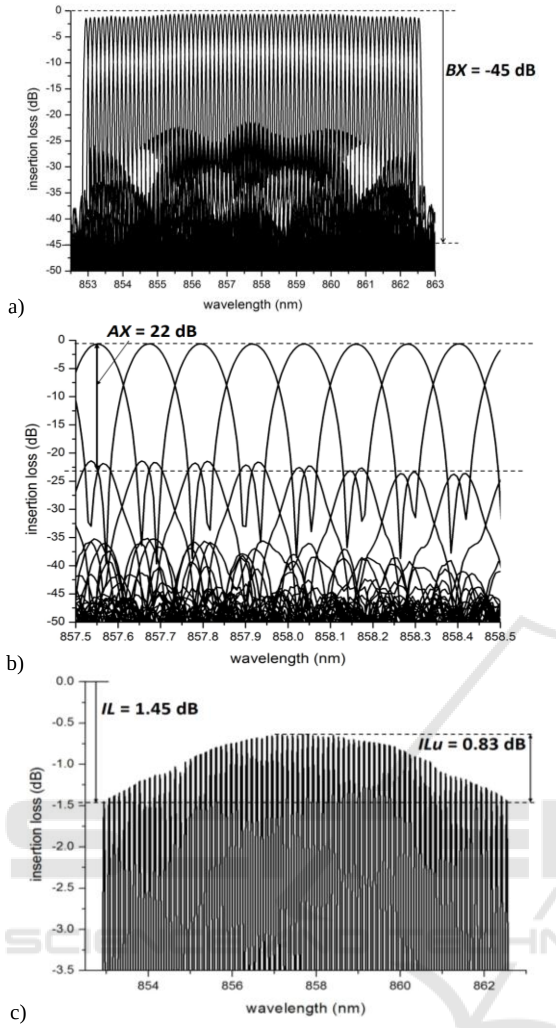

Figure 6: DESIGN2 - a) Simulated spectral response of 80-ch, 50-GHz Si_3N_4 AWG; b) detailed view of the adjacent channel crosstalk, *AX* in the middle of the spectrum, c) detailed view of the insertion loss, *IL* and insertion loss uniformity, *ILu*.

5 DISCUSSION

Table 1 summarizes the most important performance parameters calculated from all four optical responses:

- **Insertion Loss (*IL*):** As described in section 3, decreasing the minimum waveguide separation between PA waveguides (parameter *dd*) led to a strong reduction of the insertion loss, *IL*. This is in particular the case of 40-channel, 50-GHz AWG (*dd* = 1.2 µm) that reached the loss *IL* = -1.2 dB. Opposite to this, increasing the distance between PA waveguides, the losses increased accordingly, as can be seen in DESIGN2 (*dd* = 1.75 µm, *IL* = -1.45 dB) and in DESIGN3 (*dd* = 2.2 µm, *IL* = -3 dB). In comparison, the 80-channel, 50-GHz AWG (DESIGN1), even having *dd* = 1.2 µm, features higher losses caused by widening of the optical signals (*IL* = -2.18 dB).
- **Insertion Loss uniformity (*ILu*):** Due to the fact, that the transmitted wavelengths follow the envelope described by the far-field of the array waveguides, there will always be non-uniformity *ILu* in the intensity of focal sum-fields (Smit, 1996). Therefore this performance parameter is also used as an input parameter in AWG design (see sub-section 3.1), which was set to *Lu* = 1 dB (Fig. 2). The non-uniformity calculated from the simulated spectral responses is similar to this value in all designs. Here, the small deviations are the result of the calculation accuracy.

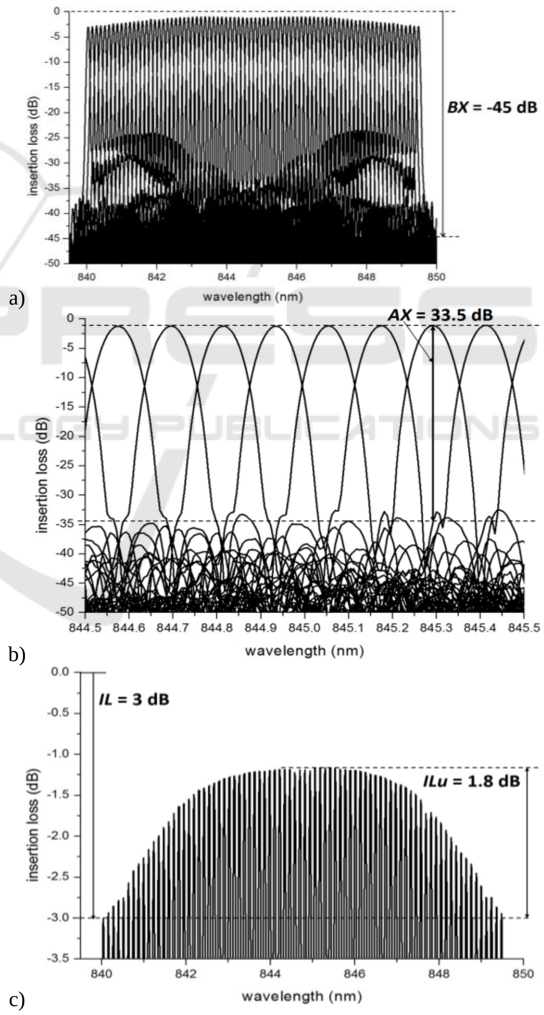

Figure 7: DESIGN3 - a) Simulated spectral response of optimized 80-ch, 50-GHz Si_3N_4 AWG, b) detailed view of the adjacent channel crosstalk, *AX* in the middle of the spectrum, c) detailed view of the insertion loss, *IL* and insertion loss uniformity, *ILu*.

- **Adjacent Channel Crosstalk (*AX*)**: the highest channel crosstalk between the neighbour output waveguides (*AX* = 11.8 dB) was reached in DESIGN1 with the widest shape of optical signals. Since the other designs (40-channel, 50-GHz AWG, DESIGN2 and DESIGN3) feature similar spectral responses also the calculated channel crosstalks are similar to each other (*AX* = 22-23 dB) and they all are much lower compared to DESIGN1. Lower channel crosstalk means higher channel isolation.
- **Background Crosstalk (*BX*)**: this parameter follows the adjacent channel crosstalk parameter, *AX*, i.e. the worst value was reached for the DESIGN1 (*BX* = -38 dB). All other designs reached similar values ensuring much higher background isolation.

Table 1: Performance parameters calculated from all optical responses.

	IL (dB)	*ILu* (dB)	*AX*(dB)	*BX*(dB)
40-ch AWG	**-1.2**	**1.18**	**23.8**	**-42**
DESIGN1	-2.18	0.9	11.8	-38
DESIGN2	**-1.45**	**0.83**	**22**	**-45**
DESIGN3	-3	1.8	23	-45

6 CONCLUSIONS

We showed that the design of standard channel count AWGs (up to 40) is relatively easy and ensures good AWG performance, too. Increasing the channel counts (> 40 channels) leads to the deterioration of optical properties like higher insertion loss and, in particular, higher channel crosstalk. This appears due to widening of the optical signals caused by light coupling between PA waveguides. To avoid this effect, the minimum separation between arrayed waveguides has to be increased, i.e. the PA waveguides have to be placed further apart. However, it is important to point out that the greater distance between PA waveguides means the higher losses. Therefore, the DESIGN2 is the most suitable since this AWG has optical properties the closest to optimized 40-channel, 50-GHz AWG.

Finally, based on this study we designed 160-channel, 50-GHz AWG having the optical properties very similar to 80-channel, 50-GHz AWG. All high-channel AWG designs are going to be technologically verified. Based on the measured data, the next step is the design of 320-channel, 42-GHz AWG.

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