Designing and simulating an AWG spectrometer on a SOI platform

Michele Lagioia, Peter Harmsma, Pavol Bodis, Kemo Agovic, and Mirvais Yousefi

TNO IenT, Dept. of High-Precision Semiconductor Equipment, Stieltjesweg 1, 2628 CK Delft, The Netherlands

An Arrayed Waveguide Grating (AWG) is a wavelength-based dispersive device capable of combining or separating light signals at different wavelengths. The contribution of this publication is twofold. Firstly, we review the design procedure of an AWG for integrated spectrometry applications and simulate its transmission spectrum on a Silicon On Insulator (SOI) platform at a center wavelength of 1550 nm by means of an off-the-shelf BPM solver. Secondly, we present an in-house, user-friendly software tool for parametrically optimizing the device geometry and export it directly into ASCII format for lithographic fabrication.

Introduction

When compared to other sensing principles, optical sensing is considered as having a major impact in terms of higher sensititvity and lower level of invasiveness on the surrounding environment. Moreover, recent advances in silicon photonics [1] have shown that, in comparison with other optical integrated technologies like III-V, the Silicon-On-Insulator (SOI) technology platform allows low-cost CMOS-compatible waferscale fabrication processes of integrated optical devices and devices with smaller footprints. These characteristics make SOI devices such as integrated biosensors [2], environmental sensors [3][4] highly suitable for on-chip smart systems where ubiquitous and real-time sensing capabilities are required.

For these systems-on-chip, key devices are integrated microspectrometers [5]. For such devices, there is normally the attempt to strike a balance between footprint, spectral resolution and spectral range, depending on the particular application. Spectral resolution can be achieved via design, but is still limited by the fabrication processes, which for SOI on-chip spectrometers [6] have been shown to be reproducible and uniform [7]. Moreover, properly engineering a SOI microspectrometer allows covering the whole spectral range where silicon and oxide are transparent (1.2-3μm).

In this paper, we present our results on design and simulation of an Arrayed Waveguide Grating (AWG), a device widely used in telecommunication applications [8] and recently adopted for on-chip spectrometry. Secondly, we show a user-friendly software tool to optimize the device size and export it to a mask-layout file.

Performance considerations

The operation of an AWG, sketched in fig. 1, is such that an input light beam is diffracted through the first free propagation region (FPR) onto the input aperture, which consists of an array of waveguides, whose length differences are designed in such a way that the mutual optical path length difference is an integer multiple of the central wavelength λ_0. In this way the phase front on the input aperture at λ_0 is perfectly reproduced on the output aperture. The second FPR allows the field to converge and focus in the middle of the image plane, where an output waveguide is placed. A wavelength shift of the input field provokes a linear phase shift along the output of the array and the consequent shifting of the focal point on the image plane, so that light will couple to a different output waveguide. A thorough explanation of the parameters influencing the performance of the AWG can be found in ref. [8]. The performance of an AWG is normally influenced by different parameters. A flat-band response is crucial for multiplexing because it allows better wavelength control, while for spectrometry this is not required. Insertion losses can be due to coupling from the first FPR to the array (and reciprocally from the array to other diffraction orders), but also to propagation losses in the waveguides and, principally, abrupt (non-tapered) transitions between array waveguides and FPRs. Those issues can be only slightly solved via design, while the use of tapers (preferably with shallow etching [7]) at the array-FPR interfaces decreases the overall losses considerably. Inter-channel crosstalk can be reduced by increasing the pitch d_o between adjacent output channels at the expense of spectral resolution. Since the field on the image plane is the Fourier transform of the input field, the field truncation due to the finite width of the array aperture, causes an increase of the side lobes of the focal field, which produces additional crosstalk. For this reason, the whole input aperture needs to be illuminated. Beyond these two mechanisms, the major part of crosstalk is caused by phase errors due to fabrication imperfections on the array waveguides; therefore it is convenient to design shorter waveguides.

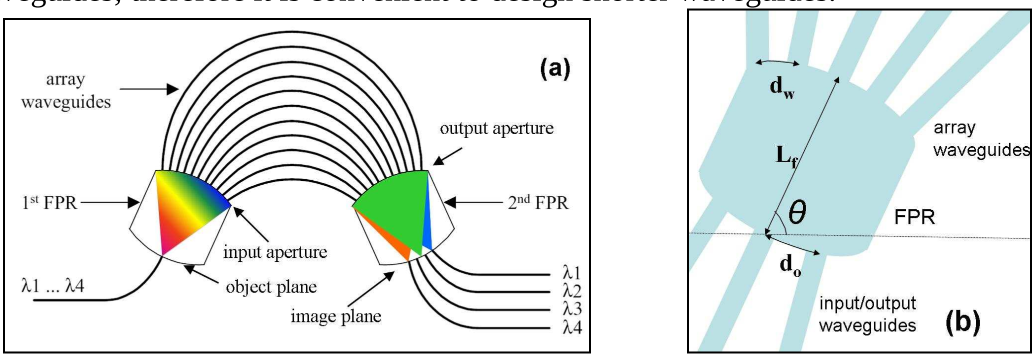

Figure 1: Schematic representation (a) of an AWG and its working principle (a broad-spectrum light beam is decomposed in a few spectral components) and geometrical parameters of a free propagation region (b).

Design and simulations

Our design is optimized for the TE polarization and we consider a 220nm thick silicon layer and 450nm wide waveguides, supporting only the fundamental TE mode.

Due to the influence of fabrication parameters on overall losses, in order to simplify the design steps, we do not consider insertion losses as a design specific, but in order to reduce them we use tapers on the array waveguides at the input/output apertures, where the gaps between adjacent tapers are fixed to 150nm, achievable with CMOS-compatible lithography. To minimize inter-channel crosstalk, we fix d_o to 2μm, while to address crosstalk for truncation, we optimize the array illumination. Thus the analytical specs are just channel spacing $\Delta\lambda_{ch}$, central wavelength λ_0 and the number of output channels N_o. The design steps are summarized as following: **1)** deduction of the free spectral range $\Delta\lambda_{FSR} = N_0 \Delta\lambda_{ch}$, **2)** computation via mode matching method (FMM) [9] of the group n_g and effective n_{eff} indexes of the waveguides and the effective index n_{slab} of the FPRs, **3)** calculation of the diffraction order of the array $m = \lambda_0 n_{eff} / (\Delta\lambda_{FSR} n_g)$, **4)** deduction of the length differences of the waveguides $\Delta L = m\lambda_0 / n_{eff}$ and the lengths of the FPRs $L_f = d_o d_w n_{slab} \lambda_0 / (\Delta\lambda_{ch} \Delta L n_g)$, with d_w (set to 1.5μm) pitches between the array waveguides at the input/output apertures.

Using these parameters, to optimize the array illumination and the overall transmission, simulations with the beam propagation method [10] (BPM) have been carried out. The BPM method is preferred to other methods like FDTD because it allows more efficient simulation of components with large cross sections and lengths, like the FPRs of the AWG. On the other hand, BPM is not as accurate as FDTD or FMM when simulating high-index contrast systems like SOI, and this strongly influences the dispersive response of the array. Thus, for choosing the proper number of array waveguides, we repeatedly simulate the dispersion from the input waveguide to the array, and find roughly 100 waveguides as optimum. Finally the transmission spectrum is calculated and, as can be seen in figure 2(a), the loss on the transmission peak is less than 5dB (reducing the gaps between array waveguides tapers would further improve it), while crosstalk is roughly -20dB and $\Delta\lambda_{ch}$ of 1.5nm. In order to reduce the size of the AWG, we halved N, and accordingly doubled d_w (to keep the array illumination unchanged) and ΔL (to keep $\Delta\lambda_{ch}$ constant). Using the layout shown in the inset of figure 2(a), we reduced the overall size by roughly 25% while keeping the same response, shown in figure 2(b). The final size was approximately 1.5x1.5 mm^2.

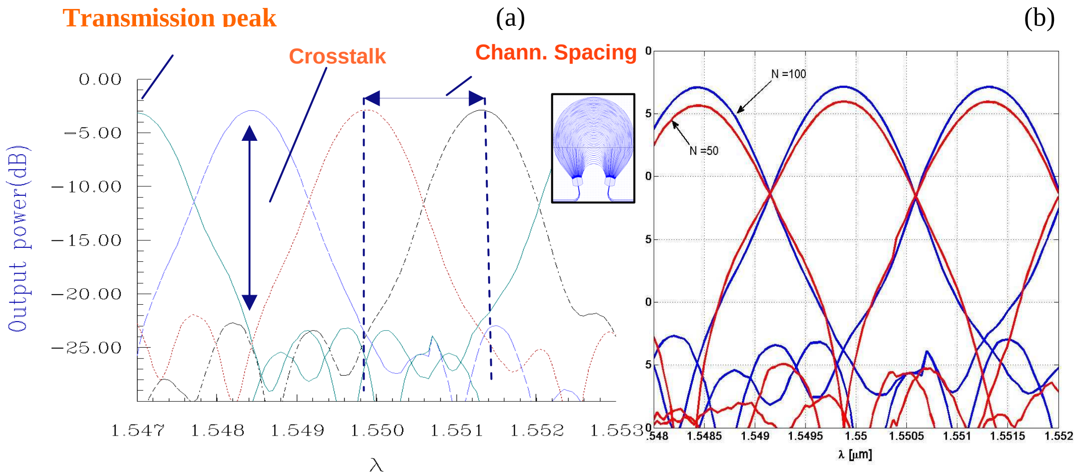

Figure 2: Simulation results in terms of transmission spectrum for an AWG with 100 array waveguides (a) and comparison with a smaller AWG, with 50 array waveguides, doubled distance and length difference between array waveguides (b). The footprint of this latter is 1.5x1.5 mm^2.

Layout tool for geometrical optimization

For a particular layout, decreasing N comes to expenses in terms of ΔL, which increases the probability of fabrication errors on the array waveguides and consequently the crosstalk. Thus, in order to manually optimize the geometrical layout of an AWG, we introduce a Matlab® tool with a graphical user interface (shown in figure 3), which enables to view, live, the influence of some geometrical parameters (FPR orientation angle θ, number of array waveguides N, separation between the FPR tips and length of the shortest array waveguide) on the layout. Other geometrical parameters, including tapered sections and input/output connections, can be set off-line. More importantly, the tool allows exporting the complex structure of an AWG, with respective mask layers numbers, to a file in ASCII format, which can be easily imported by common mask layout software packages. Additionally, the tool can import tapers which are proximity-corrected, for e-beam lithography, and replace them properly on the existing layout. Finally, the tool can be expanded to account for other layout styles of the array in order to reach smaller ΔL and consequently a larger spectral resolution.

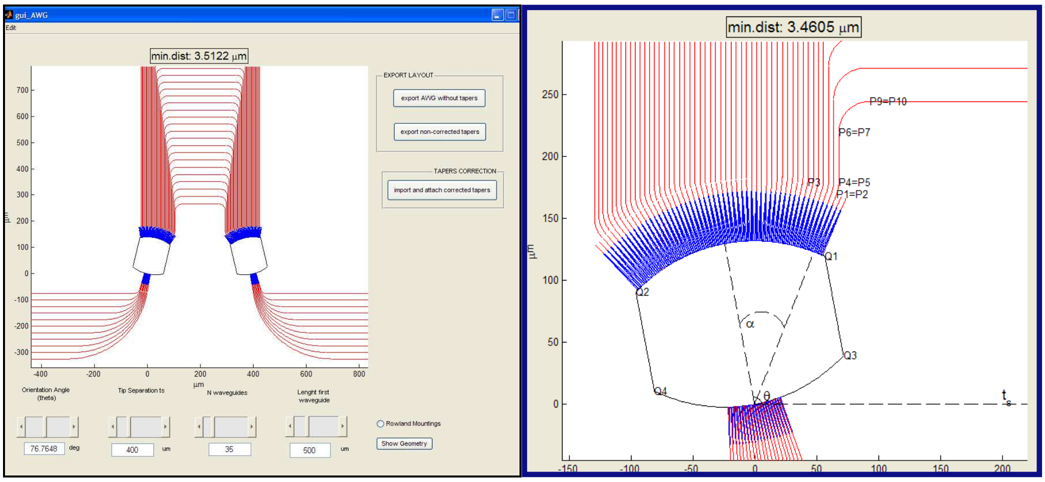

Figure 3: Screenshots of the GUI tool for the design of the layout of the AWG

Conclusions

After a review of design considerations on an AWG spectrometer, we propose a design strategy, which beyond analytical equations, includes numerical simulations of the field diffraction in the free propagation regions in order to reduce crosstalk. We simulate the transmission spectrum at a center wavelength of 1550 nm and achieve a spectral resolution of 1.5nm, with a crosstalk better than -20dB and insertion losses of -5dB. Moreover, we present a powerful tool to reduce the size of the array, and consequently reduce phase errors. The tool allows optimizing parametrically the device geometry and exporting it directly into a file in ASCII format for lithographic fabrication.

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