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Flat-focal-field integrated spectrometer using a field-flattening lens

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Abstract - *We present a new flat-focal-field arrayed-waveguide-grating (AWG) design that utilizes an integrated field-flattening lens placed in the second star coupler. The effective-index difference between slab and lens region is obtained by introducing a thin silicon nitride layer to a silicon oxynitride environment. As a proof-of-concept 81-channel AWGs, with and without the lens, are designed, fabricated, and characterized. The measurements show that the adjacent crosstalk at the peripheral channels is improved by 2 dB and only 0.4 dB of extra excess loss is introduced by the lens. A more pronounced crosstalk-improvement for AWGs with higher number of output waveguides is predicted.*

Introduction

Integrated spectrometers applied in sensing, imaging, and telecommunication are usually of the Rowland mounting type in which the input and output waveguides are located on the arc of the so-called Rowland circle [1]. This arrangement has the advantage of reduced aberrations compare to other mount configurations and is useful whenever output channels guide the wavelengths diffracted by the spectrometer to their desired destinations, because the output channels can be arranged on the same curved image plane. Such a curved image plane, however, is not well suited for applications in which the output spectrum shall be continuously imaged directly onto a linear detector array [2,3]. Opposed to a curved image plane which would result in additional losses and aberrations at the outer detector channels, in this case a flat image plane would be desirable.

A spectrometer with a straight imaging plane is called a flat-focal-field spectrometer. Such spectrometers solve the aforementioned problems associated with Rowland mounting type spectrometers. Different methods were proposed for the design of a flat-focal-field grating spectrometer with limited success [4,5]. In this work, an alternative way of designing a flat-focal-field arrayed waveguide grating (AWG) [6] using an integrated field-flattening lens located in the second star coupler will be presented.

Design

In an ideal optical system (one without any aberrations), a planar object will be imaged onto a curved surface instead of a plane in the paraxial region. This aberration is known as Petzval field curvature [7]. A field-flattening lens is a thin plano-concave negative lens which is placed close to the image plane of an optical system to flatten the curvature of its image surface by minimizing the Petzval aberration [7]. In an AWG, the field curvature induced by the second star coupler (considered as a positive convex lens) can be compensated by placing a field-flattening lens in the second star coupler just before the output waveguides. By being close to the image plane it minimally affects the other aberrations.

In order to image each point on the curved surface onto a flat image plane, the focus should be shifted as a function of the lateral position *y* of the image point. This condition necessitates a (field-flattening) lens thickness which is a function of the lateral position *y* of the image point as well. The radius of curvature R_f of the field-flattening lens can be derived as [8]

$$R_f = \left(\frac{n_2 - n_1}{n_2}\right) R_r , \tag{1}$$

where n_2 and n_1 correspond to the effective refractive indices of the lens and the slab region.

Three AWGs were designed, one without a field-flattening lens, and two with different lens designs, all having a free spectral range of 64.8 nm and a resolution of 0.8 nm. Output waveguides were used in order to make a direct comparison between measurement results of AWGs with and without lens. The lens structures were not on the same mask. This allowed the fabrication in two runs of four devices in total: AWGs with their output waveguides arranged on a straight line, both with and without a field-flattening lens. The two devices without lens made it possible to check for unwanted process variations. The schematic of the field-flattening lens in the second star coupler is shown in Fig. 1a.

For the AWGs with field-flattening lens, the index difference between slab and lens region was introduced by applying a thin silicon nitride (Si_3N_4) layer in the lens region.

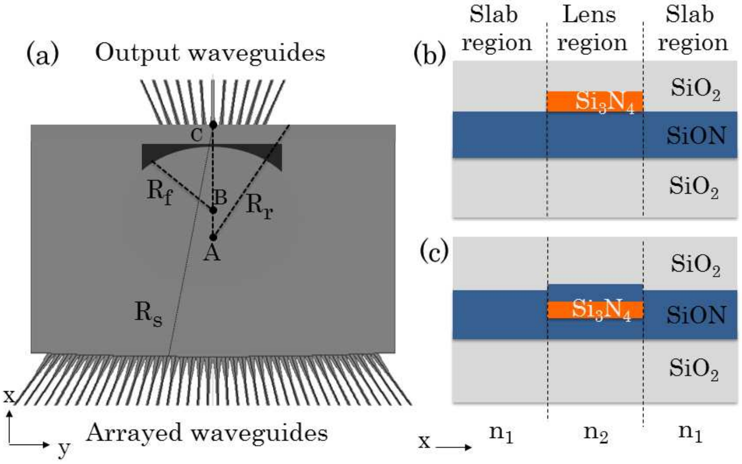

Fig. 1. (a) Field-flattening lens in the second star coupler of the AWG. R_r, R_s, and R_f are the radii of curvature of the Rowland circle, the slab region, and the lens, respectively. **(b)** Cross-section of the star coupler with silicon nitride (Si_3N_4) layer on top of the silicon oxynitride (SiON) layer, or **(c)** with Si_3N_4 between SiON layers. n_1 and n_2 are the effective refractive indices of the slab region with and without Si_3N_4 layer, respectively.

Two different lens designs were implemented; one with a 160-nm-thick Si_3N_4 layer deposited on top of a 1-µm-thick SiON layer (Fig. 1b) and one with a 120-nm-thick Si_3N_4 layer sandwiched between 500-nm-thick SiON layers (Fig. 1c). In the latter design the SiN layer thickness was reduced (120 nm) in order to obtain the same effective refractive index in the lens region and thereby the same lens radius for both designs. The thickness of the Si_3N_4 layer was chosen as a compromise between excess loss and minimum lens size providing full coverage of all output waveguides. According to BPM simulation results, the latter design performed better in terms of mode-mismatch-induced excess loss, which was calculated to be

0.9 dB whereas it increased to 2.6 dB in the former design. The radius of curvature R_s of the grating circle was 5531 µm. The effective indices of the slab and the lens region were calculated to be 1.50 and 1.61, respectively, which results in a lens radius of R_f = 189 µm.

Characterization

The performance degradation of an AWG due to a non-compensated flat output plane, i.e. without a field-flattening lens, was investigated by comparing its BPM-simulated transmission responses with those of a conventional AWG (outputs placed on the Rowland circle). The results are shown in Fig. 2.

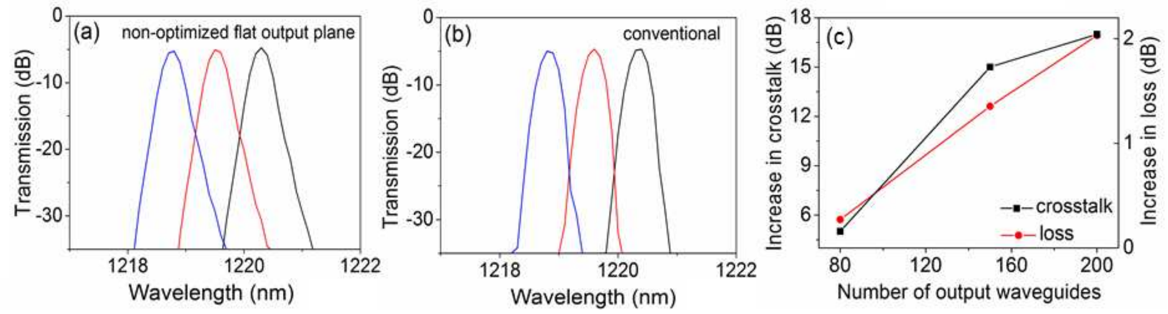

Fig. 2. Simulated effect of using a non-optimized flat output plane in an AWG. **(a-b)** 80-Channel device, edge channels (1-3) of **(a)** the flat-output-plane AWG without optimization, and **(b)** the conventional AWG. **(c)** Increase of crosstalk and loss versus number of output channels.

Without field-flattening lens, large aberrations will be introduced, resulting in high adjacent crosstalk, additional insertion loss, and broader spectral shape at the outer channels. The simulations predict that the AWG with non-optimized flat output plane exhibits degradation in adjacent crosstalk, spectral shape, and insertion loss performance. An excess loss value of 0.5 dB and a 5-dB decrease of adjacent crosstalk was introduced at the outer channels. Such problems become more severe for AWGs with a large number of output waveguides (~2 dB of excess loss and ~16 dB of decrease in adjacent crosstalk for 200 output waveguides) as shown in Fig. 2c.

The performance improvement by the field-flattening lens was demonstrated by comparing the crosstalk, spectral shape, and insertion loss of the four AWGs, as shown in Fig. 3. For the lens design shown in Fig. 1b the adjacent crosstalk was improved by 5 dB and an excess loss value of 2.5 dB was introduced by the lens due to high mode mismatch. For the lens design given in Fig. 1c the adjacent crosstalk was improved by 2 dB and an excess loss value of only 0.4 dB was introduced by the lens. The non-adjacent crosstalk values of -30 and -25 dB and excess loss values of 0.5 and 4.5 dB were measured for the central and outermost channels, respectively. A center wavelength shift of 17 nm was found to be caused by a higher than designed SiON refractive index and an incomplete etching of the Si_3N_4 layer (~15 nm of residual) in the regions where no lens structure was applied. The incomplete etching also resulted in a smaller index difference (n_2-n_1) between the slab and the lens region and BPM simulations confirmed this to reduce the experimentally observed improvement of adjacent crosstalk from 6 dB to 2 dB. Although the demonstrated improvement of adjacent crosstalk is rather small, it is expected to be easily improved by optimizing the fabrication procedure.

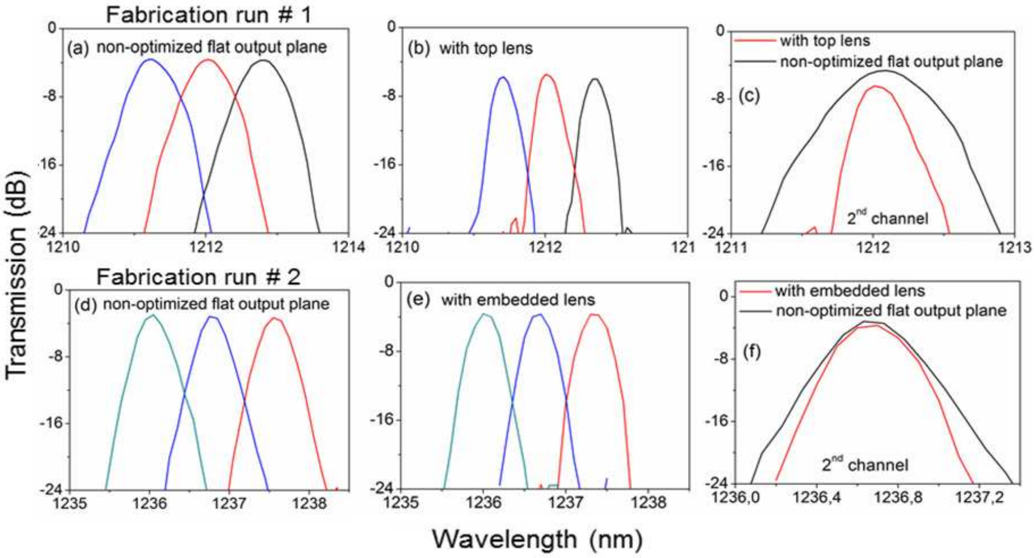

Fig. 3. Transmission measurement results for some edge channels of the realized AWGs: **(a, b, c)** the first fabrication run and **(d, e, f)** the second fabrication run. **(a, d)** with a non-optimized flat output plane **(b, c)** with a field-flattening lens where Si_3N_4 layer on top of SiON layer, and **(e, f)** with a field-flattening lens where Si_3N_4 layer embedded between SiON layers.; **(c, f)** comparison of the results given in **(a, b)** and **(d, e)** for the 2nd channel.

Conclusion

A novel flat-focal-field AWG using an integrated field-flattening lens was designed, fabricated, and characterized. Although the current improvement in adjacent crosstalk was smal, the impact of the lens is expected to be more pronounced for AWGs with a higher number of output waveguides. The flat image field of these AWGs enables one to directly butt-couple them to a detector array, making this design very attractive for applications such as optical coherence tomography and Raman spectroscopy.

Acknowledgement

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