## Photonics at Mikroelektronik Centret

### Introduction

The photonics group at Mikroelektronik Centret (MIC) works in close collaboration with industry to do research on photonic components. Advances are being made in three major areas: diffractive optics, passive waveguides and active waveguides. Most of the components find application within telecommunications and some are used for optical sensors. Recently, a new company IONAS was established based on our research results and collaboration with Danish industry. In the following we describe some of our research projects in more detail.

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# Multiwavelength DFB fibre laser source

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### Abstract

We describe the development of distributed feedback (DFB) fibre lasers based on UV-induced fibre gratings. The lasers are single-mode, have a linewidth smaller than 15 kHz and a signal to noise ratio better than 61 dB. The stability of the lasers is verified by a 10 Gbit/s transmission experiment. Five DFB fibre lasers are cascaded and pumped by a single semiconductor laser, thereby forming a multiwavelength source for optical telecommunication.

### Introduction

In the following we describe results from a research project concerning grating based fibre lasers. Stable single mode laser sources with narrow linewidth are attractive for several applications such as optical communication and sensor systems. UV induced distributed feedback (DFB) [1,2,3] and distributed Bragg reflection (DBR) [4] fibre lasers are very compact and able to provide stable single-mode operation with narrow linewidth and excellent signal to noise ratio. They exhibit a tuning range of several nanometer with continuos single mode operation as well as a low temperature drift. We present a multiwavelength laser source consisting of 5 fibre DFB lasers spliced together and pumped by a single 60 mW 1480 nm semiconductor laser.

### Experiments

Each laser is fabricated individually using 5 cm of an erbium doped fibre spliced to standard fibre pigtails equipped with angled connectors. The Bragg gratings are photoinduced using a KrF excimer laser illuminating a 5 cm long phasemask with 248 nm light. The fluence on the fibre is around 0.4 J/cm$^2$. The grating growth was monitored during writing using an erbium doped fibre based broadband source. After around 3000 pulses the transmission dip was measured to be 20 dB. The actual length of the grating is 4.6 cm. A grating strength *kL* of around three was calculated from the transmission dip. After the writing process is completed, the grating is optically pumped by a semiconductor laser giving 60 mW at 1480 nm. A phase shift is induced in the central part of the grating by additional UV-exposure while the lasing is monitored on an optical spectrum analyser. To verify single mode operation we use a scanning Fabry-Perot interferometer with a free spectral range of 7.5 GHz [2].

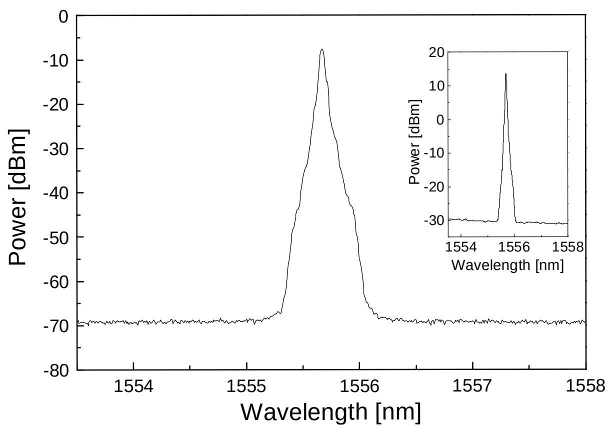


*Figure 1. Lasing spectrum of a DFB fibre laser measured with a resolution of 0.05 nm showing a signal-to-noise ratio of 61 dB. The insert shows the amplified signal.*

The lasers show excellent stability. During all further experiments the laser was packaged in a block of aluminium which was mounted on the optical table. Further temperature stabilisation was not necessary as the wavelength drift due to temperature is as low as 0.01 nm/K.

To prove the long term stability of the laser a transmission experiment was carried out at a bit rate of 10 Gbit/s. A DFB fibre laser was modulated externally with a $2^{31}$ -1 non return to zero pseudo random bit sequence using a Mach Zehnder modulator controlled by a 10 Gbit/s transmission error test set. The signal was transmitted over 49.5 km of non dispersion shifted standard telecommunication fibre with a total loss of 10 dB. Error free operation was observed during a measurement time of one hour.

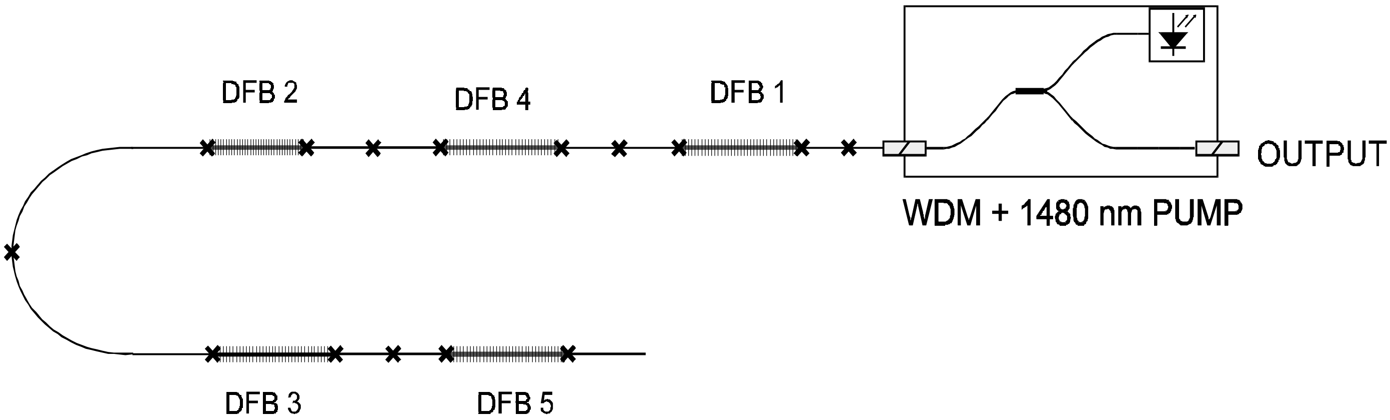


*Figure 2. Experimental setup for the five wavelength DFB fibre laser source (crosses indicate fusion splices).*

During the UV inscription of the grating it is possible to apply stress to the fibre. This leads to a shift of the centre wavelength of the grating when the fibre is released after UV inscription. The highest lasing wavelength is obtained when there is no stress applied on the fibre during the writing process. The lowest obtainable wavelength with one phasemask is determined by the maximum stress the fibre can endure during the exposure. One single phasemask hereby allows a tuning range of around 5 nm. Within this range the wavelength reproducibility of our current set-up is around 0.2 nm.

### Results and Discussion

When we characterise the output of the lasers with a double monochromator optical spectrum analyser (OSA) with a resolution of 0.05 nm, we find no signs of side-modes. As an example Figure 1 shows the lasing output of a 4.6 cm DFB fibre laser pumped by 60 mW of 1480 nm light. The signal power is around 150 mW at a peak wavelength of 1555.6 nm. The spectral shape is the response of the OSA to a linewidth which is more narrow than the resolution of 0.05 nm. The smooth background is suppressed by 61 dB. Eventual side-modes appearing within the resolution of the OSA are well below the detection limit of the scanning Fabry-Perot interferometer. The output was found to be linearly polarised. When amplifying the laser with a commercially available booster amplifier to a signal power of 22 mW, a signal to noise suppression of 44 dB can still be maintained (see inset Figure 1).

Polarisation and longitudinal single-mode operation has been verified continuously without mode-hopping from room temperature up to 200 °C. Single mode operation was also confirmed at -196 °C. Similar to other DFB lasers our lasers have a narrow linewidth [5,6]. Measurements using the delayed self-heterodyne method [7] revealed a linewidth below 15 kHz.

Four more lasers were fabricated using the above described method. After verifying single mode operation of each laser, the angled pigtails were cut off and the lasers were spliced together and pumped with 60 mW of 1480 nm light (see Figure 2),

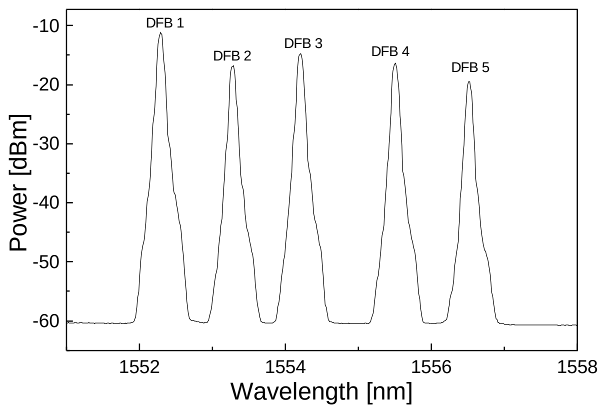


*Figure 3. Optical spectrum of the multiwavelength DFB fibre laser source, measured with 0.05 nm resolution.*

forming a multiwavelength source. The peak wavelength separation is 1.0 nm ± 0.1 nm . Figure 3 shows the 5 lasing peaks. The difference in lasing power is mainly due to relatively low pump power in combination with not fully optimised splicing. The amplified spontaneous emission of each piece of erbium doped fibre as well as the relatively weak pumping also contributes to a decrease of the signal to noise ratio to around 45 dB.

### Conclusion

We have presented polarisation and longitudinal single-mode DFB fibre lasers based on UV-induced Bragg gratings with a permanent phase shift. The lasers show a peak power of 150 mW, a signal to noise ratio of more than 61 dB, a linewidth less than 15 kHz, and stable continuous single mode operation from room temperature to 200 °C without mode-hops. In a 10 Gbit/s transmission system error free operation through 49.5 km of standard fibre was observed. Five lasers with a peak separation of around 1 nm were spliced together to form a multiwavelength DFB fibre laser source. These results demonstrate that DFB fibre lasers can be considered as an alternative source in WDM telecommunication systems. The robustness of the single mode operation combined with the narrow linewidth make them equally well suited for wavelength multiplexed sensor systems and spectroscopy.

### Acknowledgements

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## Fabrication of fibre terminated planar waveguides

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### Introduction

Planar, silica-on-silicon based waveguide components have received much attention recently, especially as components for dense WDM systems. At Mikroelektronik Centret (MIC) processes have been developed for fabricating planar waveguides. The waveguides have propagation losses around 0.1 dB/cm.

Several functional waveguide devices have been fabricated at MIC as described elsewhere in this issue.

An important requirement for the planar waveguide technology to be commercially useful, is that fibre termination of devices must be possible in a simple way. The fibre termination has to be stable and must ensure an efficient coupling of light. Processes have been developed to fabricate waveguide devices integrated with fibre guiding grooves for fibre termination. Fibre pig-tailed components have been fabricated with connection loss less than 0.5 dB/connection and with a back-reflected power of less than -35 dB.

### Fabrication

The components fabricated at MIC are of the buried waveguide type. The waveguides are fabricated in phosphorous and germanium doped silica glass materials (PSG and GePSG). The fabrication is a sequence of glass depositions, photolithography and etching of structures. The glass materials are deposited by PECVD, and the etching is performed by Reactive Ion Etching (RIE). A schematic view of the process is shown in Figure 1. The figure shows a wafer cross section at different steps in the process.

The buffer has a thickness of 15 µm and has a refractive index close to undoped silica. A 6 µm thick layer of core glass doped with germanium is deposited on top of the buffer as shown in

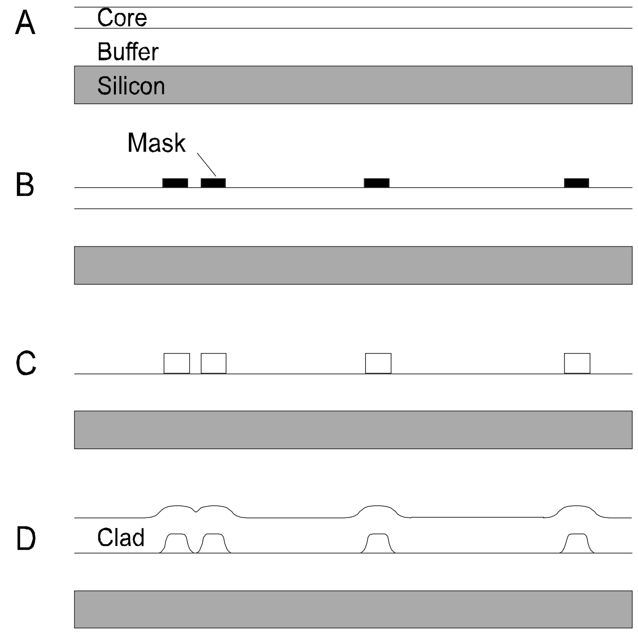


*Figure 1: Cross section of a wafer going through the fabrication process:*
*A) The buffer and core glass layers are deposited by PECVD. B) The core structures and the groove structures are defined through photolithography. C) The structures are etched by RIE. D) A cladding glass layer is deposited over the cores and the structure is eflown.*

Figure 1.A. The glass layers are annealed in a furnace to relax the stress and to diffuse out hydrogen from the deposited layers. The waveguide pattern is transferred to the wafer through standard photolithography, Figure 1.B. Then the core structures are etched. After etching the mask is removed by another reactive ion etch process, Figure 1.C. The top cladding is finally deposited by PECVD and reflown at 1100 °C, Figure 1.D. The cross section of the buried planar waveguide resembles the cross section of an optical fibre.

Fibre termination can be achieved by means of fibre guiding grooves which are integrated in the silicon substrate. These grooves can be fabricated with high precision to guide fibers to the right position in front of the waveguides. Processes have been developed at MIC to fabricate such waveguide components. A groove is positioned at the end of each waveguide, with the center of the groove matched to the center of the waveguide. The fibre termination is performed by placing fibres in the grooves so that the position of the fibre cores and the waveguide cores are matched precisely.

The fabrication process is shown schematically in Figure 2. The waveguides are fabricated as discussed above. In Figure 2.A the buffer and the core layers have been deposited, and the waveguide core regions are defined through photolithography. Fiber guiding grooves are defined in the same mask level. The core structures and the groove structures will be etched into the core glass layer. In Figure 2.B the masking layer has been removed and the top cladding glass layer has been deposited. A second mask layer is then deposited and patterned. This mask defines the facets of the waveguides. The groove structure in this mask level is wider than in the first mask level, and the groove width is therefore determined by the first mask level. In Figure 2.C the glass layer has been etched through to expose the silicon substrate. There will still be some microns of the original structures left at the edges of the grooves. The facets of the waveguides are formed through this etch process. In Figure 2.D the grooves have finally been etched into the silicon. A SEM micrograph of a fibre guiding groove in front of a waveguide is shown in Figure 3.

### Results and discussion

The fabricated waveguides have been characterized with respect to propagation loss and fibre termination. The propagation loss is measured with light at 1.55 μm in a setup with a butt coupled fibre at both input and output. The measurements show loss around 0.1 dB/cm. The fibre termination is characterized with respect to precision of the grooves and the coupling of light.

The transverse offset of the fiber when inserted into the grooves is given by the depth of the groove and the width of the groove. The width of the grooves is defined in the lithographic mask and is therefore mainly a design issue. This leaves the process for etching the grooves as the main challenge with respect to fiber alignment. Work has been done to understand and optimize the

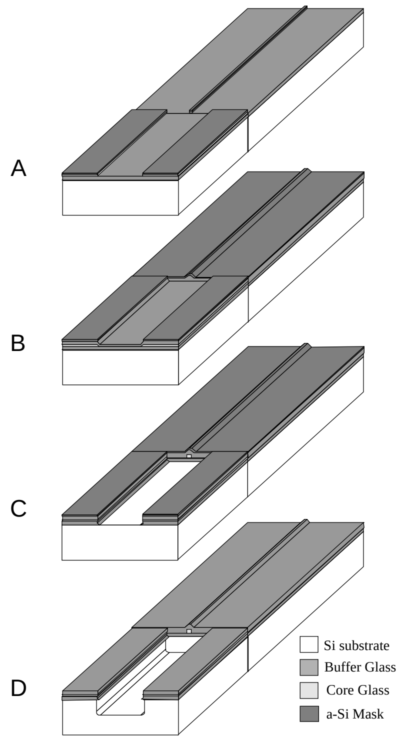


*Figure 2: A schematic view of the fabrication process for planar waveguide components with fiber guiding U-grooves. The process steps are discussed in the text.*

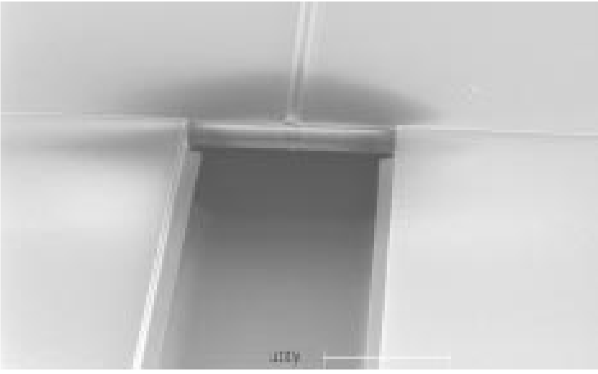

*Figure 3: A SEM micrograph of a fibre guiding groove in front of a waveguide.*

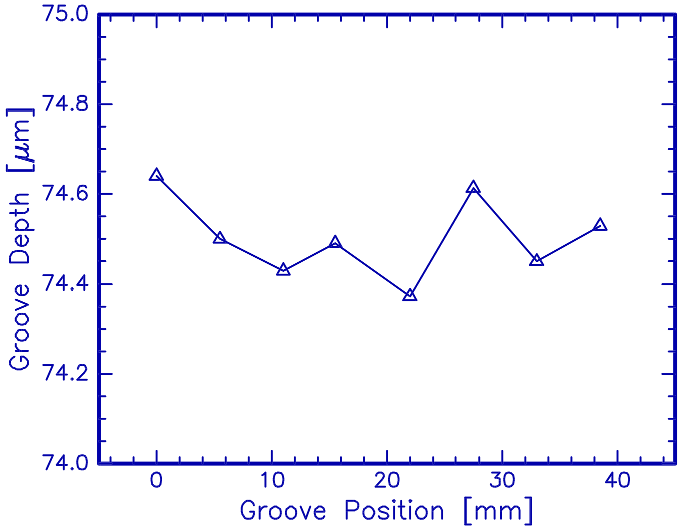


*Figure 4: Measured groove depths across a 4 cm wide array of fibre guiding grooves.*

uniformity in the silicon etch process. Very good uniformity of the fibre guiding grooves has been obtained. The graph in figure 4 shows measured groove depth across a 4 mm wide array of fibre guiding grooves. The measured groove depth includes the glass layers and the silicon grooves. It can be observed that the depth of 74.5 $\mu $m only varies ± 0.15 µm across the entire array.

Fibres are inserted into the grooves and fixed by UV-curable epoxy. The total insertion loss and the back reflected power of the fibre terminated device can then be measured. The measurements show insertion loss in the range of 1.0 dB to 2 dB. As the waveguides are 5 cm long, this leads to coupling loss around 0.5 dB/connection if the loss is evenly distributed between the two couplings. The back reflected power is measured to be less than -35 dB for all components.

### Conclusion

Fabrication processes for planar waveguides in silica-on-silicon have been developed. Waveguides have been fabricated with propagation loss around 0.1dB/cm. Additional processes for fiber termination of waveguide devices have been developed. Fiber terminated devices have been fabricated with insertion losses around 1.0 dB and back reflected power of less than -35 dB.

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## Bragg gratings written in planar waveguides

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### Introduction

The first optically written Bragg grating has been realised in silica fibre in 1978 [1] but research and development in the field of UV-written structures really took off in 1989 when a side-writing technique was invented enabling controlled variation of the grating parameters [2]. The first Bragg grating written in single mode silica-on-silicon waveguides was realised in 1992 [3].

This paper presents the results obtained so far at Mikroelektronik Centret (MIC) with Bragg gratings written in planar waveguides made by silica-on-silicon. We first give an introduction to the basic formulae on Bragg gratings. Then we describe the set-ups used for writing gratings and give results on the different kinds of gratings studied at MIC. Finally, we give some examples of applications of Bragg gratings in waveguides.

### Principle

When exposed to UV light, some glasses show a permanent change in refractive index. This photosensitivity is exploited to induce Bragg gratings in the core of optical waveguides. Exposing the waveguide to an UV interference pattern results in a refractive

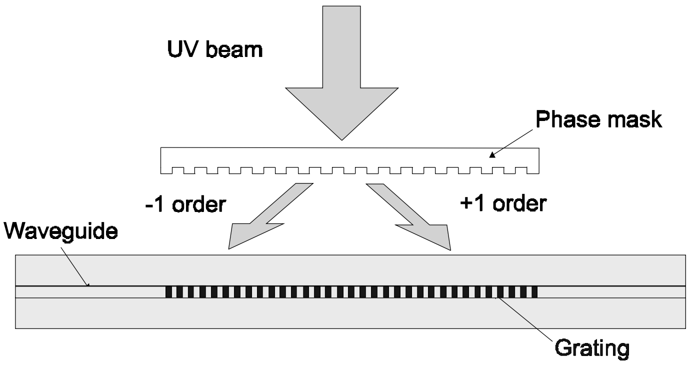


*Figure 1. Schematic of a phase mask apparatus for grating inscription.*

index modulation in the core which can be described by :

$$n(x,y,z) = n_0(x,y,z) + \Delta n(z)\cos\left(\frac{2\pi}{\Lambda_0}z + \phi(z)\right)$$

where $n_0(x,y,z)$, $\Delta n(z)$, $\Lambda_0$, $\phi(z)$ and $z$ are the average refractive index, the index modulation, the grating period, the phase variation and the direction of optical propagation, respectively. This structure reflects a wave propagating in the waveguide and fulfilling the Bragg condition:

$$\lambda_B = 2n_{eff}\Lambda_0$$

where $\lambda_B$ is the Bragg wavelength and $n_{eff}$ is the effective refractive index of the guided mode.

## Setup

Two different set-ups are currently used at MIC for writing Bragg gratings. The first configuration is a free space interferometer [2]. The UV beam is split in two equal parts that are directed by two mirrors to intersect at an angle $\Theta$, resulting in an interference pattern. The UV source used in this set-up is a CW frequency doubled argon ion laser delivering 244 nm light. By varying the angle between the interfering beams, gratings of nearly any periodicity can be produced. This method is thus very flexible but presents some drawbacks as, for example, mechanical instability, lack of reproducibility due to the precision required for the alignment and a low interference visibility.

A second method has been more recently introduced using a phase mask [4]. The corrugation at the surface of a silica plate modulates spatially the phase of the normally incident UV beam. The light is thus diffracted and the plus-first and minus-first diffraction orders interfere giving an interference pattern with a period equal to half the phase mask period (see Figure 1). This method is easy to use, very reproducible and less demanding in terms of spatial coherence of the UV source. Therefore an excimer laser delivering 193 nm or 248 nm light can be used to inscribe gratings. The pulsed laser beam is powerful enabling illumination of a large area.

## Results

The set-ups described above may be used either for optical fibres or planar waveguides. In this paper we will focus on Bragg gratings written with the phase mask technique in the planar waveguides realised at MIC [For further description of these waveguides read the article written by B. A. Møller et al. and

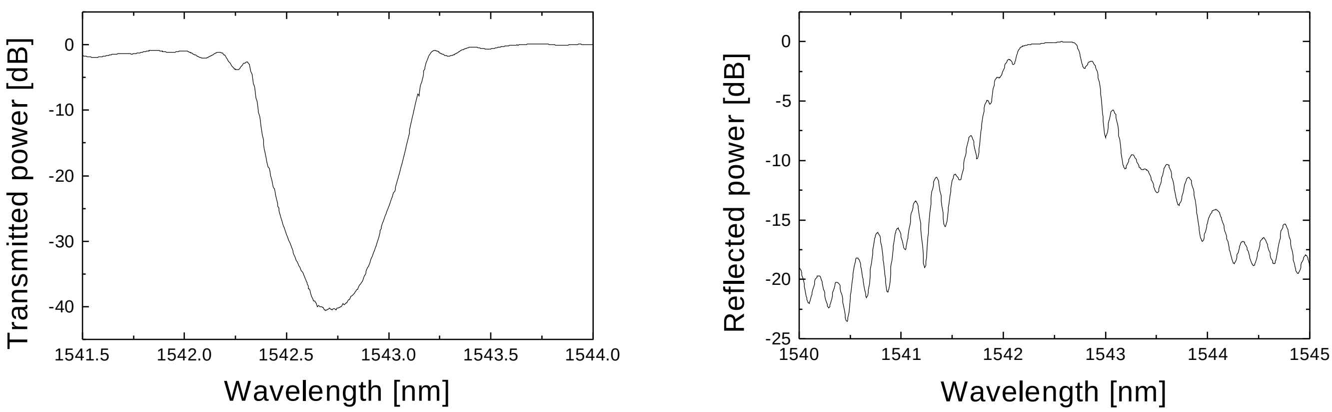


*Figure 2. Transmission and reflectance spectra of a 5 mm long uniform grating.*

published in this issue].

The photosensitivity of the glass deposited by PECVD is high, but can be increased further by placing the waveguides in a deuterium chamber at high pressure for several days [5]. Without this sensitisation strong gratings can nevertheless be obtained [6], but the deuterium loading allows a growth of the gratings which is several orders of magnitude faster [7].

By adjusting the different parameters of the Bragg gratings, e.g. the length and the index modulation, different filter functions may be achieved.

for WDM components.

All these different gratings have also been demonstrated in optical fibres. But planar waveguides present important advantages compared to optical fibres. They first offer higher stability and are easier to handle. Moreover, because of the different geometry, the phase mask is closer to the core than for optical fibres leading to higher visibility of the UV interference pattern in the waveguide core [10]. Another advantage is that the cladding mode distribution is different in planar waveguides compared to standard optical fibres, preventing strong outcoupling situated at the short wavelength side of the Bragg gratings.

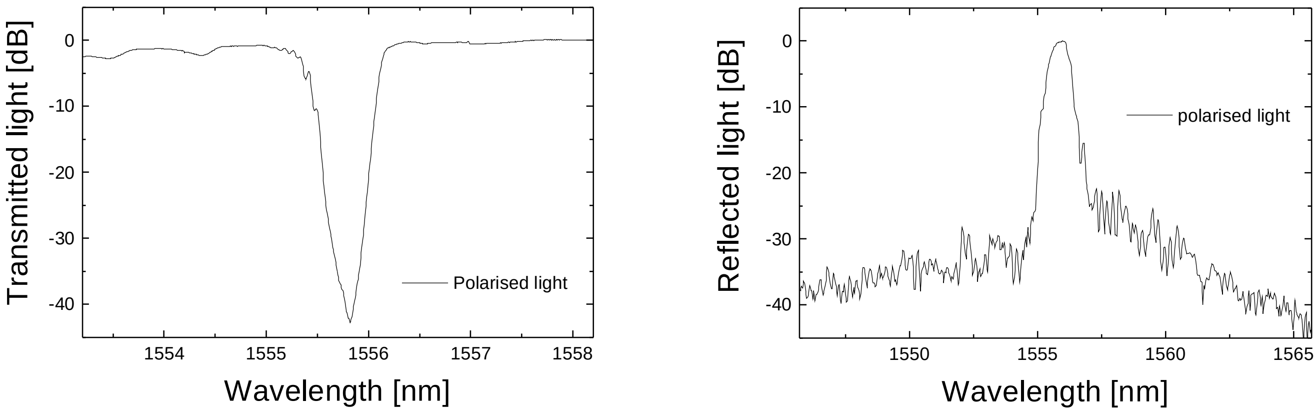


*Figure 3. Transmission and Reflectance spectra of a 7 mm long apodised grating.*

A uniform Bragg grating is obtained by illuminating the waveguide through a uniform phase mask with uniform UV light. Both the index modulation and the effective refractive index are constant along the grating. The FWHM can be very narrow for weak gratings, but sidelobes appear around the Bragg wavelength for strong reflectivity (see Figure 2)

We have demonstrated that these uniform Bragg gratings may also be a very efficient tool for the waveguide characterisation [8].

When the Bragg gratings are used in multi-wavelength systems, the filter function is often required to have a quite large bandwidth and very low background rejection. These requirements may be fulfilled by writing an apodised grating. In that case, the index modulation is varying along the grating. At MIC this apodisation is achieved by using the Gaussian shape of the UV beam intensity. If no further treatment is made, the average refractive index is also varying along the grating leading to a broadening of the bandwidth. This way, strong gratings with low background rejection and efficient utilisation of the bandwidth have been achieved (see Figure 3).

By modulating the amplitude or the phase of a conventional grating using a sampling function, one obtains so-called sampled gratings. This can be realised by inserting an amplitude mask in front of the phase mask to periodically block the beam. This way, we achieved 30 dB sampled gratings [9] (see Figure 4). The distance between the peaks is easily adjustable when varying the amplitude mask parameters. This kind of device is interesting

## Conclusion

The numerous applications of Bragg gratings have made them a subject of increasing interest worldwide. One of the most promising fields of application is within telecommunication.

Integrated optics is a very attractive alternative for realising such components. This way, multi-functional devices with high

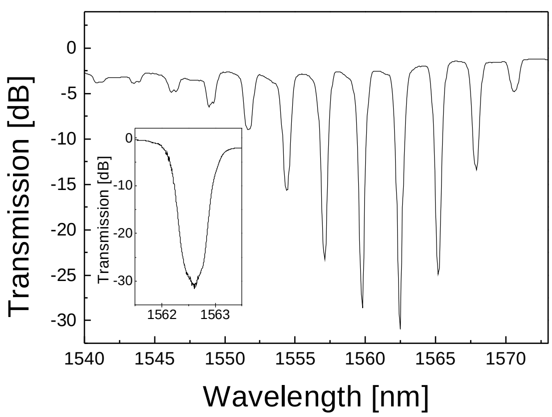


*Figure 4. Transmission spectrum of a 4.2 cm long sampled grating (sampling period = 300 mm, duty cycle = 1/5).*
*Inset : zeroth order peak.*

mechanical and thermal stability can be realised.

In this paper, we presented a large variety of gratings written in planar waveguides made in silica layers deposited by PECVD on silicon substrates. We realised very strong uniform gratings which may be used as stop-band filters [11]. For dense multi-wavelength networks we have developed apodised gratings and sampled gratings which may be used in WDM components [12].

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