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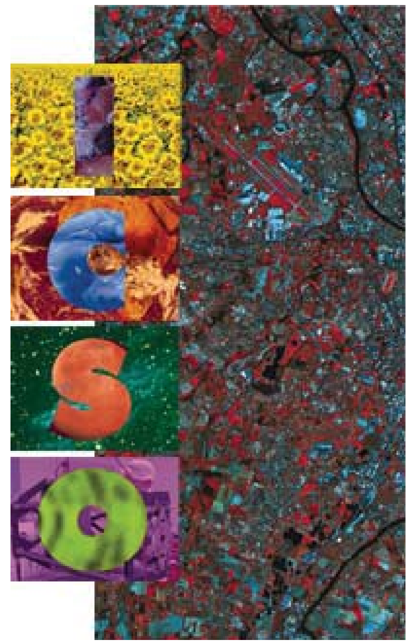

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OPTICAL WAVEGUIDES FOR 1064 nm AND CHIP PIGTAILING WITH PM FIBERS

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ABSTRACT - The purpose of this project was to develop optical waveguide technology to offer polarization maintaining (PM) components for a Nd:YAG laser wavelength at 1.064 μm. The silicon oxynitride waveguide layers were grown with a PECVD method on a silicon wafer. The waveguide height and width are 3.5 μm and 6.0 μm, respectively. A well balanced 3 dB operation was achieved with a 2×2 MMI coupler. The excess loss of the coupler was 2 dB. The polarization maintaining properties were studied by measuring the polarization extinction coefficient (PXR) of the straight waveguides and pigtailed chips. Typical PXR for a 15 mm waveguide was >18 dB. Waveguide crossings at different crossing angles were characterized in terms of excess loss and PXR. Both passive and active fiber alignment was studied to achieve low-loss pigtailing with a polarization maintaining fiber.

1 - INTRODUCTION

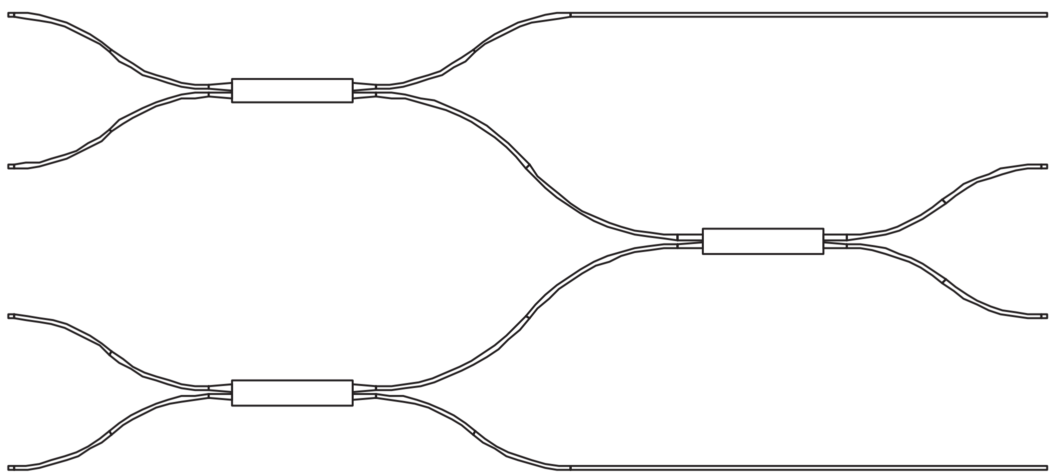
The purpose of the project was to develop optical waveguide technology to offer polarization maintaining (PM) components for a Nd:YAG laser wavelength at 1.064 μm. Couplers and splitters made of PM-fiber are commercially available but integrated optical devices offer attractive choice to enhance reliability and performance. The need for reducing system complexity and weight with integration pushes the development of planar optical devices for space applications. The short wavelength band at 1064 nm is especially interesting as compact diode-pumped solid state Nd:YAG lasers are available for free space communication purposes. Tuning the basic fabrication schemes to shorter wavelengths is challenging as surface roughness and scattering effect become more intense and cause evidently higher losses. Also the alignment tolerances become smaller as fiber and waveguide dimensions are reduced.

In this work silicon oxynitride waveguides on a silicon substrate have been studied. Various basic structures have been designed, fabricated and evaluated, including such as straight waveguides, waveguide crossings, waveguide bends, 2×2 multi mode interference (MMI) couplers and a 1×4 power splitter consisting of three cascaded 2×2 MMI couplers. The waveguide propagation loss, bending loss, waveguide crossing's excess loss, MMI coupler's unbalance and excess loss and PXR of the fabricated structures have been measured.

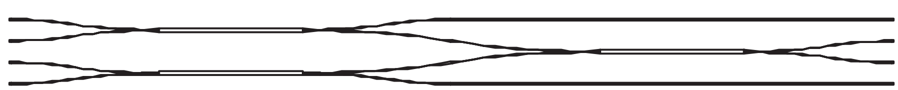
Furthermore pigtailing of the waveguide components with PM-fibers has been studied. Test pigtailing applying passive alignment and silicon V-grooves have been made. The pigtailing method applying active alignment and silicon U-grooves has been subsequently tested. The active pigtailing resulted clearly better results, as high variation of the fiber dimensions could be compensated by optimizing each fiber-waveguide coupling individually.

2 - DESIGN

The basic waveguide geometry was fixed by matching the mode field of the waveguide with the one of the PM fiber (HB1000, Fibercore Ltd.). The core's width and height were designed to be 6.0 µm and 3.5 µm, respectively. The refractive index difference (Δn) between the waveguide core and buffer layer was set to be 8×10^{-3}. The buffer and cladding layer thickness were designed to be 6 µm [1]. The device was designed to operate at TM polarisation.
An MMI coupler was designed to realize a balanced 2×2 optical coupling function. MMI couplers width and length were designed to be 42..44 µm and 1800 µm, respectively. These values were varied ±10% in a mask around the nominal values. The coupler was designed to operate in paired interference mode [2]. The axial distance between the feeding waveguides was varied from 14.0 to 14.7 µm. Minimum bend radius to be used within the input and output arms was selected to be 20 mm. An 8 port test device consisting of three 2×2 couplers was designed (Fig. 1). A 12 port test device with additional 2 straight waveguides adjacent to the 8-port was designed for a passive pigtailing test.



a)



b)

Fig. 1. A schematic layout of the test device consisting of three cascaded 2×2 MMI couplers. a) A highly exaggerated layout not in scale and b) an example layout in the right scale. Separation of the adjacent input and output waveguides is 250 µm. Radius of the constant curvature S-bends is 20 mm. Active area of the device is less than 1×14 mm^2.

3 - FABRICATION

Plasma enhanced chemical vapor deposition (PECVD) was used to deposit the silicon oxynitride planar waveguide structure (Fig. 2). The substrate was a 1.3 mm thick silicon wafer. Thick substrate prevents any warping due to a stressed glass layer. Before actual fabrication the deposition equipment was calibrated to adjust Δn to be 8×10^{-3}. The etching process was based on two masking layers to achieve vertical side walls and sufficient etch depth when the waveguide core was formed with a dry etching process. The etching mask consisted of a thin molybdenum layer (thickness 600 nm) covered with a thick photoresist (thickness 2.4 µm). The waveguide structure was transferred lithographically into the thick photoresist layer and subsequently the thin molybdenum layer was dry etched. Both the photoresist and the molybdenum layer were used as a mask to dry etch the oxide. The top cladding layer was deposited using PECVD. A problem generally known to result with PECVD deposited top claddings was experienced [3]. Nano-slit formation aside of the core may have caused higher propagation loss of waveguides and large excess loss of MMI couplers. The chips were sawn apart and polished for optical measurements.

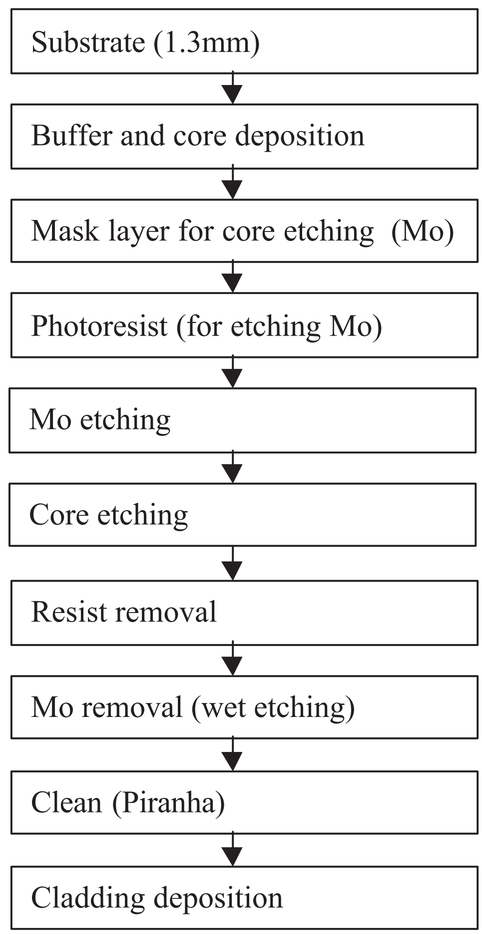


Fig. 2. Flow chart showing the main steps to fabricate the planar waveguide structure.

3.1 Fiber pigtailing

The passive pigtailing method was based on silicon V-groove blocks. PM-fibers were rotationally aligned and inserted between two V-groove blocks. 4 and 6 fiber arrays were tested with the fabricated waveguide devices. Before pigtailing the quality of the fiber batch was analyzed. The core's eccentricity was measured to vary between 1.10-1.19 µm. Due to this large variation the passive alignment was changed to active alignment. For the active fiber pigtailing special fiber supporting silicon U-groove blocks were fabricated. An oxide layer was grown on silicon wafers to act as a mask layer in deep silicon etching. The silicon etching was done with an inductively coupled plasma (ICP) equipment. The fabricated blocks were glued to the input and output facets of the waveguide device. Each fiber was individually mounted into a groove, aligned with the waveguide and fixed (Fig. 3). Final device structure with a waveguide chip and separate U-groove blocks attached to it is shown in Fig. 4.

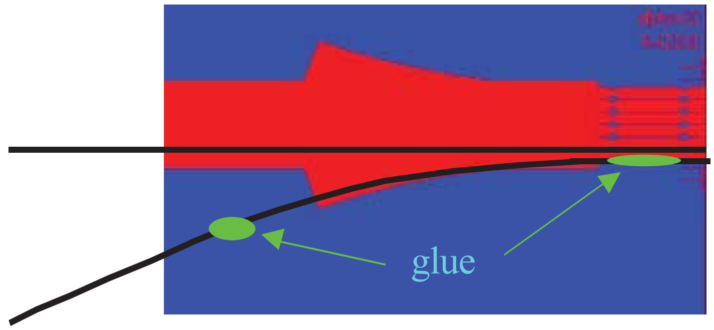


Fig. 3. A schematic top view of a fiber block being used as a platform for fiber mounting. The waveguide chip (not shown) is on the right side of the fiber block.

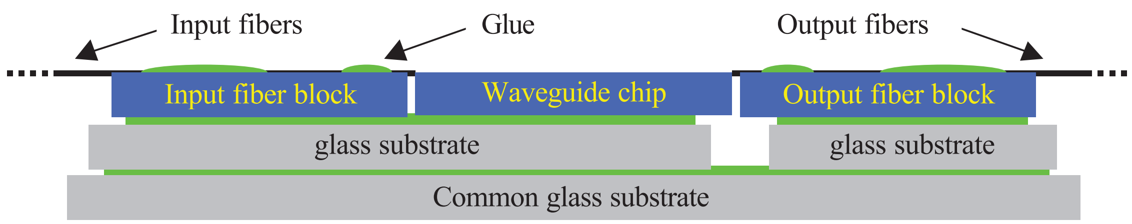
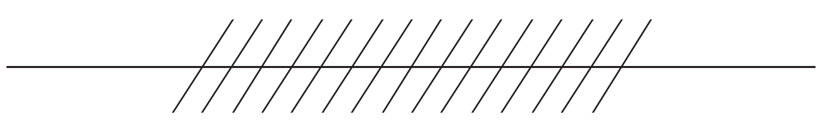


Fig. 4. A schematic longitudinal cross-section of the device structure. The thin gaps between the two chips and the three substrates have been partly filled with glue. The thickness of the substrate glass is 1.0 mm.

4 - RESULTS

Optical evaluation was made at 1064 nm. Light from a laser (PTI LCS-DTL-021) was coupled to a PM-input fiber thus that the electric field was along the slow axis. The polarization axis of the fiber was then rotationally oriented to launch TM polarization in the waveguide. Transmission was collected either with a PM- or multimode fiber. The waveguide propagation loss was measured to be 0.3 dB/cm. A waveguide crossing causes excess loss dependent of the crossing angle (see Fig. 5 and 6). Typical degradation of PXR was measured to be below 0.2 dB with a crossing angle of 20 degrees. A 90 degree waveguide bend with a radius of 10 mm was measured to have an excess loss of 0.5 dB when compared to a straight waveguide.



	α=20°	30°	40°	60°
Excess loss (dB)	0.47	0.32	0.25	0.1

Fig 5. Layout of the test structure to measure excess loss and PXR degradation due to a waveguide crossing at different angles (α). The test waveguide had 60 pieces of dummy crossings. Transmission of the intersected waveguide was referenced to a continuous waveguide aside of the test waveguide.

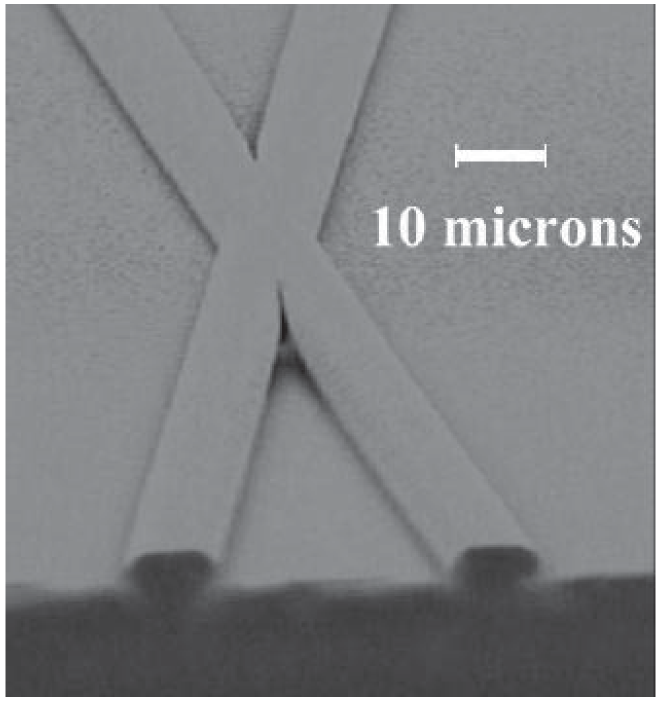


Fig 6. SEM picture of a fabricated waveguide crossing. Only negligible blunting effect is seen in the armpits of the waveguides.

4.1 Results from MMI couplers before pigtailing

Average excess loss of the 2×2 MMI coupler was measured to be 2 dB. Typical measured unbalance of the coupler was from 0.17 to 0.35 dB. An 1×4 power splitter was formed out of three cascaded 2×2 couplers (see Fig. 7). The output flatness was measured to be better than 0.2 dB (see Fig. 8).

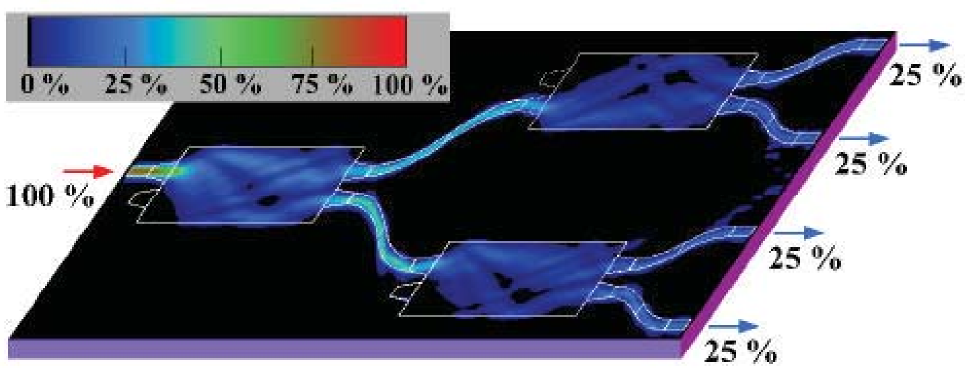


Fig. 7. Simulated optical transmission through a 1×4 power splitter based on three cascaded 2×2 MMI couplers. Intensity distribution has been calculated by using 2D BPM.

Fig. 8. Output of the 1×4 power splitter imaged with an IR-camera.

4.2 Results from pigtailed devices

Four waveguide chips were pigtailed to test pigtailing with PM fibers. Three chips were pigtailed by using passive V-groove method and one chip by using active U-groove method (Table 1). The V-groove blocks were first assembled by inserting rotationally aligned PM-fibers into V-grooves. The V-groove blocks, holding 4 or 6 fibers in an array, were then aligned with the waveguide chip and fixed with glue. Average excess loss due to the pigtailing was from 2.3 dB to 8.5dB. Serious problem was that the port transmission varied over 20 dB between some ports. The reason was the large variation of the core position of the fiber. The fiber's non-concentricity was measured to be 1.10-1.19 µm, which resulted that the core position varied in the array. With active alignment average excess loss from the pigtailing was 1.0 dB. Difference between port transmissions was still 2.8 dB (see Table 1).

chip	number of ports	pigtailing procedure	excess loss/interface [dB]		
			min	max	average
1	8	passive V-groove	4.5	37.6	8.5
2	8	passive V-groove	0.3	12.2	2.3
3	12	passive V-groove	3.4	24.8	4.7
4	8	active U-groove	0.4	3.2	1.0

Table 1. Excess loss due to the pigtailing with different methods. Three chips were pigtailed by aligning V-groove fiber arrays with waveguides and one chip was pigtailed by aligning each fiber individually.

5 - CONCLUSIONS

Basic waveguide structures have been designed for an uncommon wavelength of 1064 nm. Fabrication technology has been developed to manufacture components. Low loss waveguides have been realized with a propagation loss of 0.3 dB/cm. A well balanced 2×2 MMI coupler has been designed and fabricated. Very well balanced MMI-based power splitters can be fabricated for TM polarization. Devices have been test pigtailed to study passive and active pigtailing methods. Large variation in PM-fiber dimensions hinders applying fully passive method. Active alignment of the PM-fiber to waveguides resulted clearly lower coupling losses (excess loss 1 dB) compared to excess losses in passively aligned pigtails (excess loss >2.3 dB).

6 - ACKNOWLEDGEMENTS

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7 - REFERENCES

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