Direct UV-writing of waveguides

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Abstract

Integrated optical devices are essential for the realization of high-speed optical telecommunication networks. Direct UV writing is a novel fabrication technique for such devices, where high quality waveguides are written directly into a photosensitive glass chip. This paper describes the evolution of the UV writing method with an emphasis on practical issues.

1. Photons and chips

'Optical waveguide devices integrated on a chip are critical components for high speed optical telecommunication networks'.

That is the phrase I usually start a paper with, so I thought it might be bad luck not to use it here. Even though people in this business always start their papers somehow like this, do not think it is just an empty phrase. Without optical chips a great deal of the functions necessary to create and operate a network with hundreds of billions of bits per second in every single strand of optical fiber would not be possible. For instance, we must currently be able to interleave tens of closely spaced wavelengths of light into one fiber (wavelength multiplexing). We must also drop a datastream from a selected wavelength while adding another one in its place (add/drop multiplexing). We need to be able to manage the intensity of each wavelength, switch between different transmission paths, etc. In the past these sorts of things were done by first converting the optical signal from the fiber into an electrical signal, performing the required function electronically, and then converting the result back into light. However, the optical fiber may sustain transmission speeds so high that electronics can no longer cope with the relentless flow of bits.

In the 1990'ies the technology for making optical chips capable of such basic network functions matured to a level where the first commercial applications became possible. An optical chip consists of a substrate onto which a thin layer of transparent material has been deposited. Regions of higher refractive index (lines and slabs) in this material are used to guide light around on the chip, performing the desired network functions along the way. Optical chips are cool because they eliminate the need for conversion between optical and electrical signals. This permits the construction of telecom networks with data transmission rates many times larger than would otherwise be possible.

So far, the most successful technique for fabricating optical chips utilizes a silicon wafer as substrate and silica glass, with various co-dopants, as the transparent medium. By using this material system we can build upon the very successful and extensive work already performed for the business of fabricating integrated electronic chips. In addition, the high degree of stability of silica permits a stable device performance over decades of operation in hot, humid and dirty environments. At the Microelectronics Center and the COM Center, both at the Technical University of Denmark (DTU), the techniques and know-how for fabricating optical chips were established in the 1990's. Part of this research operation was commercialized in 1997 with the formation of IONAS A/S, a subsidiary of NKT Holding A/S.

2. Why UV write your waveguides?

Fabrication techniques currently employed by the industry, see Fig. 1a, start out by growing a so-called buffer layer of thermal oxide on the silicon wafer. Next, a core layer is deposited by plasma enhanced chemical vapor deposition. The core layer is co-doped with a few mole % germanium (Ge), which increases the refractive index by a small amount, typically 0.005–0.01. The desired waveguide pattern is defined in the core layer by photolithography and reactive ion etching. The resulting channel waveguide cores, measuring roughly 6 by 6 µm, are then covered with a final layer of glass called the cladding layer. This entire process is very sensitive towards dust contamination and must therefore be carried out in a cleanroom.

In parallel to the development of such fabrication techniques at DTU other people there worked on the topic of Bragg gratings in optical waveguides, and I was one of them. We realized gratings by exposing Ge-doped fibers to a ultraviolet (UV) interference pattern, thereby creating a longitudinal index modulation in the fiber core. The technique relies on the phenomenon of photosensitivity where intense UV radiation around ~240 nm can permanently increase the refractive index of Ge-doped glass. In late 1993 it occurred to us that we might be able to use UV radiation not just to make index modulations in waveguide cores, but instead to actually make the waveguide cores themselves. The idea was to make in the cleanroom a three-layer glass sample, consisting of buffer-core-cladding layers. The core layer should contain Ge, making it photosensitive. Outside the cleanroom we would then scan the sample underneath a focused continuous-wave UV laser beam in a pre-determined pattern, thereby directly writing lines of higher index into the core layer, without disturbing the surrounding buffer/cladding layers shown in Fig. 1b. For such 'direct UV writing' of buried channel waveguides to actually work requires that the UV induced index change be in the 10^{-3} to 10^{-2} range, yielding waveguides with an index contrast similar to that made with the fully cleanroom based techniques. The motivation for using UV writing to make waveguides is to minimize the need for cleanroom processing, which is expensive and demanding. In addition, since the waveguide layout is defined by a computer controlled scanning process it may be changed rapidly, making this technique very flexible and well suited for rapid development of new waveguide circuits.

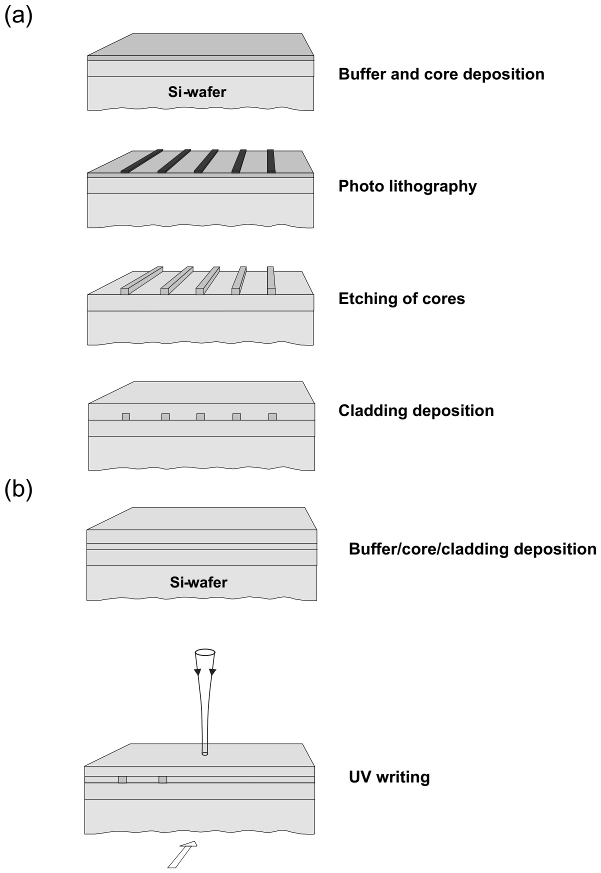

Fig. 1. (a) This is how integrated optical chips are fabricated in the cleanroom at IONAS A/S. (b) The concept of direct UV writing. Here all three glass layers are deposited without the need for photolithography or etching. The waveguide cores are then written sequentially into the core layer by scanning the sample under a focused UV laser beam.

In 1994 we first demonstrated that 'direct UV writing' of waveguides actually worked.[1] In the following years, we showed that a wide variety of waveguide devices could be UV written with a performance that was not too far behind that achieved with the conventional techniques in the cleanroom.[2,3] In 1997, with these results in hand, I caught the interest of the newly funded IONAS A/S together with Statens Teknisk Videnskabelige Forskningsråd (STVF) to support a multi-year research program targeted at improving the UV writing technique in particular and improving our basic understanding of UV induced processes in general. Both IONAS A/S and STVF continue to support the research program to this day.

3. How to do?

The UV writing setup is situated at the COM center at DTU and is being used both by IONAS A/S and COM for research and development purposes. The setup includes the following elements.

UV source and beam handling:

The UV radiation comes from a frequency doubled argon-ion laser emitting at a wavelength of 257 nm. The wavelength is not particularly important as long as it overlaps with the rather broad 240 nm absorption band associated with photosensitivity of Ge-doped silica. Hence, many of the more compact deep UV sources currently on the market may also be used. The UV beam enters what we call the 'optical delivery system', which is an arrangement of mirrors and simple lenses. The purpose of the optical delivery system is to deliver a focused beam with a stabilized direction and power onto the sample. In our current configuration we expand and spatially filter the UV beam before it enters an objective, which focuses the beam onto a sample. The setup produces a spot on the sample 3 µm in diameter at the $1/e^2$ level with a total power of 40 mW. Computer controlled mirrors and lenses in the setup combined with a power detector and beam profiler permit automated alignment of the setup. The computer system can also counteract drift in the beam direction and power throughout the fabrication process.

Sample preparation:

As mentioned previously, it is essential to be able to UV induce a refractive index change approaching 0.01. This is many times larger than needed for Bragg grating applications. However, without such index changes the confinement of the guided mode becomes too poor. To facilitate such large index changes we enhance the photosensitivity using a technique called deuterium loading.[4] Loading with deuterium is done by subjecting samples to molecular deuterium (D_2) at a pressure of several hundred bar for a few days – do not try this at home and especially do not smoke while doing so!. In this process D_2 molecules diffuse inertly into the glass matrix. Upon UV irradiation the D_2 dissociates and reduces the Ge–atoms, thereby forming what is called 'Ge-related oxygen deficient centers'. Such oxygen deficient Ge sites are responsible for the photosensitivity and are normally not very common in the glass. With D_2 loading we can make sure that essentially every single Ge–atom in the glass can be reduced and thereby participate in the index change process. The result is a photosensitivity enhancement of roughly two orders of magnitude. Since the D_2 loading occurs by *in-diffusion* we will, when the sample is removed from the high pressure environment, immediately have *out-diffusion*. This will gradually reduce the photosensitivity back to the low level it was initially. Since the diffusivity generally decreases exponentially with temperature it is possible to slow down the outdiffusion to negligible levels by storing loaded samples in a deep freeze (–80 °C or even lower).

Sample chamber:

During UV writing the sample must also be kept at a low temperature, or else the gradually decreasing photosensitivity due to D_2 out-diffusion will give us a hard time trying to reproduce anything.[5] A UV writing run typically lasts a few hours so fortunately we do not have to cool down the sample to the level used for storage. A temperature of –30 °C will suffice. This is done by mounting the sample on a metal plate, which is thermoelectrically cooled. To avoid ice formation the sample is enclosed by a vacuum chamber operating below 10^{-4} bar. This is easily achieved with an inexpensive, mechanical vacuum pump. The UV beam enters through a silica window. An illustration of the sample chamber in action is given in Fig. 2.

Scanning stages:

In order to write the desired waveguide pattern the sample chamber is mounted on two computer controlled DC stages. The stages are mounted in an x–y configuration and have an absolute accuracy of 0.1 µm. Sub-micron positioning accuracy is necessary to ensure a high degree of reproducibility of the fabricated optical devices. The stages have a travel range of 100 mm in

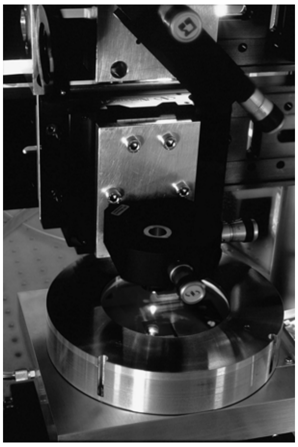

Fig. 2. Fire at will! This is the central part of our UV writing setup – the sample chamber – in action. The UV beam is directed downwards by a mirror, focused by an objective and enters the sample chamber through a silica window where it meets the photosensitive sample.

each direction, enough to cover the entire useful area of a 5 inch silicon wafer. The typical scan speed when writing waveguides is ~200 mm/sec. A lower scan speed results in a larger index change and a slightly wider waveguides. Usually, the UV writing parameters are chosen so as to yield ~6–7 mm wide waveguides with an index step of ~0.007. Such waveguides exhibit robust single mode operation at the preferred wavelengths for telecommunication (~1.55 μm), low propagation loss and low birefringence.

A close-up image of the actual UV writing process is shown in Fig. 3. After the UV writing is complete the wafer is annealed at 80 °C for 24 hours, whereby residual D_2 diffuses out of the glass. The wafer is then diced into individual chips, which can finally be characterized for optical loss and spectral response.

Note that the UV writing method is a sequential fabrication technique, i.e., the waveguides are written one at a time as opposed to the cleanroom techniques where all waveguides are fabricated in parallel. This is the main disadvantage of UV writing, since it requires us to maintain a high degree of stability in our setup for the duration of the writing session. Only after the implementation of sample cooling and computer control of the beam delivery setup have we achieved a stability which approaches the level needed for commercial applications.

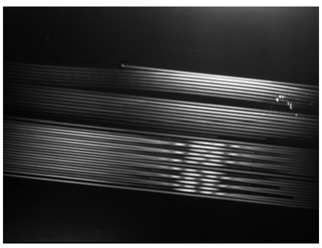

Fig. 3. A close-up view of the UV writing process. The UV beam is coming vertically down from above, making a blue spot of luminescence on the sample. Waveguides visible as bright lines are written directly into the core layer by scanning the sample. The lower part of the view shows a series of power splitters, alternating in direction.

4. Addicted to boron?

In the early days of UV writing the core layer had a refractive index that was roughly 0.01 higher than in the surrounding layers due to the Ge-doping. This index step is comparable to that of the UV written waveguides, and hence the guided mode experiences an index step in the vertical direction, which is roughly two times larger than in the horizontal direction. The result is a highly elliptical mode profile, see Fig. 4a, which is a serious problem when you want to couple light from the waveguide into a standard telecom fiber, which has a circular mode profile. Consequently, early UV written waveguides had a coupling loss of ~1–2 dB to the fiber. These values are more than an order of magnitude too large for real life applications, where optical losses must be minimized. The solution to this problem was demonstrated in 1995,[6] where British researchers added boron to the germanium-doped core layer. Where germanium increases the refractive index boron lowers it. By balancing the amounts of germanium and boron a photosensitive core may be achieved, which has the same refractive index as that of the surrounding layers. We call this an index matched sample. The guided mode of a UV written waveguide will then experience the same index step regardless of direction and hence be circular, see Fig. 4b. In 1997, we started using this technique and quickly demonstrated coupling losses 10–100 times lower than before.[7] We have been hooked on boron ever since when making low loss chips for telecom applications.

5. Variable losses

We have previously shown that basic waveguide components such as 1×2 power splitters and 2×2 directional couplers[3] may be fabricated with UV writing. These components may serve as building blocks for more complex, commercially interesting devices. In the following, I will summarize our results regarding the de-

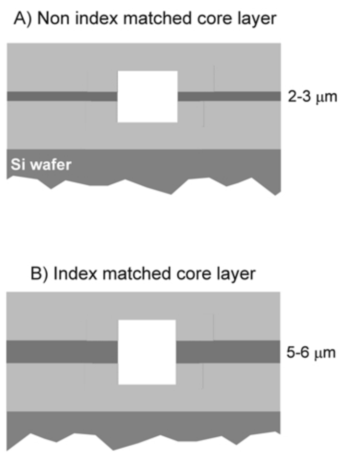

Fig. 4. (a) In non index-matched samples the core layer has a refractive index, which is higher than the surrounding glass layers. An image of a guided mode profile from a UV written waveguide is shown superimposed on the glass structure. The mode is highly elliptical since the index step in the vertical direction is larger than in the horizontal direction. (b) By co-doping the core layer with boron the core index may be tailored to match that of the surrounding layers. In such a sample the guided mode profile becomes more circular. The core layer can also be made thicker, thereby better matching the core dimensions of an optical fiber.

velopment of one such device, namely a broadband variable optical attenuator (VOA).

VOAs are essential in optical networks for such functions as channel blocking and power management. Especially power management is important since the wavelength channels carried in a single fiber must be kept at similar power levels. For such applications VOAs are deployed at wavelength (de)multiplexing nodes where they can regulate the signal strengths of individual channels (channel equalizing). Since the factors determining the signal strength are subject to change we need attenuators that can be varied according to an external, electrical input. The VOA should also preferably be a broadband device, since it is not desirable to build a product range containing an enormous range of slightly different components.

The layout[8] of the VOA pursued in this work is shown in Fig. 5. Two 1×2 power splitters with an arm spacing of 80 µm are connected head on to form a Mach-Zender interferometer (MZI). Thermooptic (TO) phaseshifters consisting of gold electrodes (12 mm wide, 10 mm long) are located on the top cladding, directly above both arms of the interferometer. By applying a current to one of the TO-shifters we can induce a phase delay, which determines the MZI transmission. The dynamic range is the ratio between the maximum and minimum transmission loss. By adding up normalized field amplitudes in the output arm, it may be shown that the dynamic range can be written as:

$$\text{dynamic range [dB]} = -10 \cdot \log\left[\left(\frac{\sqrt{s_1 s_2} - \sqrt{(1-s_1)(1-s_2)}}{\sqrt{s_1 s_2} + \sqrt{(1-s_1)(1-s_2)}}\right)^2\right], \qquad (1)$$

where s_1, s_2 is the relative power fraction directed by the left and right splitter into adjoining paths. Hence, when $s_1 = 1-s_2$ (point symmetrical configuration) the dynamic range would ideally be infinite. However, if one considers the loss of the VOA due to mismatching splitters ($s_1 \neq s_2$) in a similar manner as above, it may be seen that only when $s_1 = s_2 = 0.5$ we get a device, which does not loose power at field recombination. Therefore, our goal is to utilize splitters that divide the signal equally into the interferometer arms.

Each splitter consists of three sections: an input arm, a lower output arm and an upper output arm. The sections are scanned sequentially, starting with the input arm, followed by the upper output arm and finally the lower output arm. Each scan starts at a central branching point and moves outwards, as indicated by arrows on the schematic overview in Fig. 6. Each output arm consists of an 800 µm straight section, tilted 0.2° from the input arm, followed by circular arc s-bends. The output arm spacing is 80 µm and the length if each splitter is roughly 3 mm.

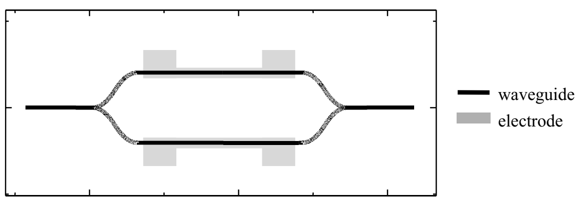

Fig. 5. Schematical layout of a variable optical attenuator (VOA).

Since we want a symmetrical power distribution in the splitter arms we initially applied the same scan velocity (200 µm/s) in all three arms, since we expected this to result in a device, which is completely symmetrical around the longitudinal axis. However, measurements showed that splitters written in this way exhibited a splitting ratio of ~0.70 (the relative amount of transmitted power contained in the first written output arm). This asymmetry must be due to a lower refractive index of the arm written in the second scan. Subsequent analysis showed that the second written arm had an index step being a few times 10^{-4} lower than that of the first written arm. We traced this behavior to be caused by a slight reduction in photosensitivity in the vicinity of a previous scan. To achieve symmetrical devices therefore requires us to apply a lower scan velocity in the second written output arm, compensating for this effect, see Fig. 7. At ~70 µm/s in the second arm we achieve a splitting ratio of 0.5. From Fig. 7, we also see that there is a significant scattering in the splitter performance. This is most likely due to uncontrolled variations in the UV beam power and direction. This is one example of the current limitations of UV writing, compared to other more established fabrication techniques.

Each VOA is written using a total of six scans. Making the waveguides meet head on in the middle of the interferometer is not a problem since the stages have an accuracy of 0.1 µm, ~60 times less than the waveguide width. The processing time for one VOA is ~4 minutes, meaning that we can make hundreds of them pr. day. When the UV writing is completed we deposit the gold electrodes on the glass surface using a standard technique based on e-gun evaporation and sputtering. Finally, the wafer is diced out into individual chips, which are 22 mm long and 4 mm wide. Each chip contains 8 VOA's along with a few straight waveguides for reference purposes.

For evaluation, light from a polarized 1557 nm laser is coupled through the VOA using butt coupled, standard single mode telecom fibers. This results in a measurement of the fiber-to-fiber loss, the so-called insertion loss (IL). Due to the sample geometry, with a very thin glass film on a silicon wafer, the maximum and minimum loss occurs for either the transverse electric (TE, electric vector parallel to the substrate) or the transverse magnetic (TM, magnetic vector parallel to the substrate) polarization mode. Loss curves are measured as a function of the power applied to one of the electrodes, with a typical result shown in Fig. 8. The transmission coefficient varies as sine squared with the phase delay; a theoretical expression incorporating this behavior has been fitted to the measured data (line curve). The minimum loss is less than 1 dB and the dynamic range is ~30 dB.

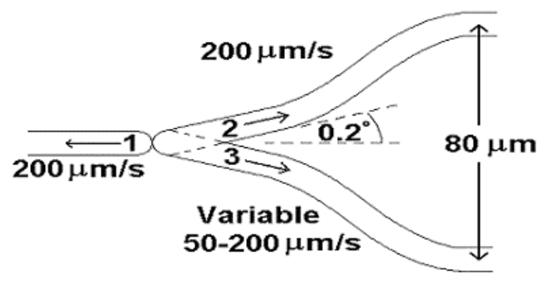

Fig. 6. Close-up of a 1×2 power splitter. The structure is written in three scans, each starting at the branching point and moving outwards.

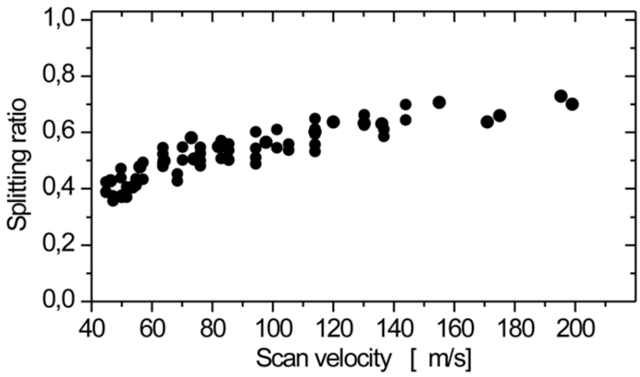

Fig. 7. Splitting ratio versus the scan speed applied in the lower output arm. The scan speed applied in the upper arm is fixed at 200 μm/s.

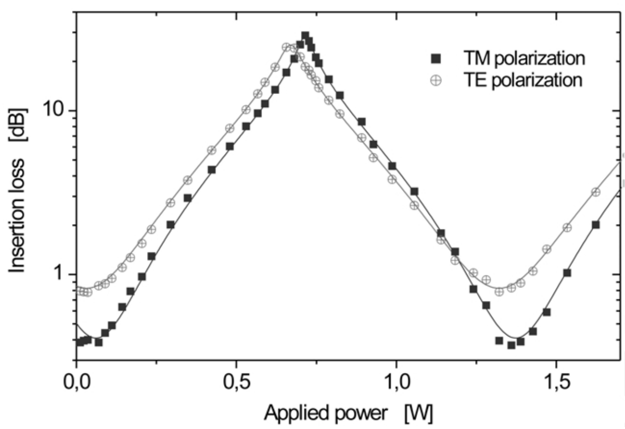

Fig. 8. VOA in action! By varying the electrical power applied to one phase shifter we can control the optical loss over a range of three orders of magnitude.

The power required for a π-phase shift is 0.65 W. The example in Fig. 8 has the minimum transmission loss when no power is applied to the electrode. If this is not desired for some specific application, we can move the loss curves along the x-axis by applying a current to the electrode over the other arm of the interferometer. Alternatively, a similar effect may be achieved by unbalancing the interferometer using UV light to induce a permanent index increase in one of the arms. This method has the advantage of minimizing the power requirements of the VOA, at the expense of an added process step.

The VOA from Fig. 8 represents a very good performance in terms of compactness, dynamic range and minimum loss. This shows that the UV writing technique may compete in terms of performance head on with other fabrication methods.

However, one problem remains: the difference between the two polarization curves. This polarization dependent loss should generally be as low as possible, since the polarization state of telecom signals varies in an uncontrolled manner. The discrepancy arises when glass heated by the electrode expands freely in the vertical direction while being restricted in doing so in the horizontal direction due to the silicon substrate. The resulting non-isotropic stress distribution leads to an elasto-optical phase shift that affects the two polarization modes differently. Hence, this problem has got nothing to do with the UV writing technique in particular. The problem may be solved by etching grooves on both sides of the gold electrode, which permits the glass to expand more freely in the horizontal direction. Another solution is to fabricate an interferometer, which is unbalanced in terms of birefringence. The birefringence in the two arms should then differ by an amount, which counteracts the birefringent effects of the thermooptic heaters. Both of these methods are currently under investigation.

6. Conclusion

UV writing has evolved from an academic exercise in materials research to a point, where commercial applications are becoming possible. We have shown that the basic waveguide performance achievable with UV writing may match that obtained with other techniques. In addition, we have demonstrated that commercially interesting, more complex interferometrical devices, such as the VOA, may be UV written with good results. One of the major remaining challenges of direct writing is to increase the uniformity and reproducibility of basic devices such as splitters and couplers. Another major challenge is to minimize the polarization dependency of more complex optical devices.

So, work still remains! I'd better get back to the lab....

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