Characterization and Optimization of Photonic Devices Fabricated Using Femtosecond Laser Micro-Machining

by

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Abstract

There is a great deal of interest and activity in the area of femtosecond micromachining of transparent materials. It promises to be a powerful technique for rapid fabrication of photonic devices in three dimensional geometries. Our group has fabricated and investigated an array of two dimensional and novel three dimensional photonic devices that are able to perform their intended functions but whose loss properties are not yet well known. The first aim of this Masters thesis is to study waveguide loss. It will focus on studying and characterizing the losses of straight and circularly curved waveguides—the building blocks of many practical devices. With a proper understanding of the loss per unit length, per unit bend angle, and per re-write of the waveguides a structured set of guidelines for device fabrication for our particular setup can be made. The second aim of this thesis is the characterization of the photonic devices fabricated and demonstrated by the author. These include a broadband characterization of directional and X couplers, as well as a demonstration of 3D symmetrical 1:N waveguide splitters for optical signal distribution.

These experimental results and discussions, which form the core of the thesis, flow in a logical fashion—from the elemental straight waveguides to the curved waveguides that are used to design the directional couplers. The X couplers provide the broadband performance that the directional couplers cannot and the 1:N waveguide splitters fabricated with the aid of an improved experimental setup not only provide a more elegant re-design of the broadband X couplers but also demonstrate scalability to N output ports in three dimensions.

Thesis supervisor: James G. Fujimoto
Title: Professor of Electrical Engineering and Computer Science
Dedicated to my parents and my sister, whom I love dearly and owe everything.
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Chapter 1

Introduction

After Schawlow and Townes had proposed the concept of the laser in their Physics Review Letter in 1958 [1], Maiman soon produced coherent radiation of visible light in ruby in 1960 [2]. This work began a new era of laser development that has made countless contributions to science and engineering. Certainly one of the most interesting advancements since then has been the development of mode-locked lasers, first introduced in 1964 [3]. These lasers, capable of generating a train of ultrashort pulses as opposed to continuous wave light, provided a new twist to the familiar source and spawned an era of their own.

The durations of ultrashort pulses have since been reduced to only a couple of femtoseconds. It is fascinating to reflect on just how small a timescale this actually is. Consider for a moment this fact: there are approximately tens times as many
femtoseconds in a second, as there are hours elapsed since the beginning of our known universe (estimated to be ~ 14 billion years old). And these minute optical pulses are not only generated but also manipulated and to some extent controlled by us for various applications. It is no doubt a very impressive feat of science of engineering, but at the same time a delightfully simple and straightforward concept to understand.

Among the numerous contributions that ultrashort pulse lasers have made, is opening the door to many nonlinear experiments. The electric field intensity requirements for many of these experiments are tremendous and modelocked short pulse lasers have been able to deliver; they spread the average output power over discrete pulses widely spaced in time that therefore contain peak powers that can be in the mega to tera Watt range.

One particularly interesting nonlinear application is the laser micromachining of glass and other transparent materials. Once focused the high peak intensity pulses generated by ultrashort lasers are capable of melting glass, which after re-solidification, experiences an increase in material density and index of refraction. This effect can be exploited to fabricate waveguides and photonic devices capable of guiding light via total internal reflection. Femtosecond micromachining not only enables high-density photonic structures, through the fabrication of multiple layers of waveguides on a single substrate, it also more importantly opens the door to a wide range of new devices fabricated in three dimensional geometries, many of which providing enhanced functionality not possible in planar geometries or producible by other fabrication techniques. Micromachining is very
Chapter 1: Introduction

versatile and promises to be a powerful technique for rapid fabrication of a wide range of photonic devices under computer control.

Our group has fabricated and investigated an array of two dimensional and novel three dimensional photonic devices. Although these devices are able to perform their intended functions and demonstrate the potential of the micromachining process, their loss properties are not yet well known. For the practical use of these devices in real world applications knowledge of their loss characteristics is of course very important. The first aim of this Masters thesis is to study waveguide loss. It will focus on studying and characterizing the losses of straight and circularly curved waveguides – the building blocks of many practical devices. With a proper understanding of the loss per unit length, per unit bend angle, and per re-trace (re-write) of the waveguides a structured set of guidelines for device fabrication for our particular setup can be made and perhaps some of the limits of our micromachining setup will be revealed. This is important so that time in the future is not invested in trying to fabricate devices with specifications that are not achievable. The second aim of this thesis is the characterization of the photonic devices fabricated and demonstrated by the author. These include a broadband characterization of directional and X couplers, as well as a demonstration of 3D symmetrical 1:N waveguide splitters. These experimental results and discussions form the core of the thesis and flow in a logical fashion – from the elemental straight waveguides to the curved waveguides that are used to design the directional couplers. The X couplers provide the broadband performance that the directional couplers cannot
and the 1:N waveguide splitters fabricated with the aid of new stages not only provide a more elegant re-design of the broadband X couplers but also demonstrate scalability to N output ports in three dimensions. A more detailed outline of the thesis chapters follows.

Chapter 2 – This chapter will start by briefly discussing the physical process of laser induced material modification. It will then give a quick overview of the development of the micromachining area from the initial demonstrations to the most current devices. This will be followed with a discussion of the machining laser sources and the two modes of operation that are currently used, and the chapter will finally terminate with an overview of the work done by our group and a description of our micromachining setup.

Chapter 3 – The focus of this chapter is to characterize curved and straight waveguides, the fundamental building blocks of most photonic devices. It will begin by first looking at the machining setup parameters used. Then propagation losses of straight waveguides will be evaluated. The effect of multiple re-writing on propagation losses will be studied. With a better understanding of the linear losses, 90° circularly curved waveguides of various radii will be fabricated and their losses estimated. The observed losses will be compared to loss estimations calculated using guided mode analysis.

Chapter 4 – Two very important 2D devices built using the elemental curved and straight waveguides characterized earlier are the directional and X coupler; both of these are very useful for optical signal distribution. This chapter will focus on the broadband characterization of the directional and X couplers fabricated by our group and specify conditions under which they perform their best.
Chapter 5 – Utilizing the full potential of oscillator based machining in transparent materials, 1:N waveguide symmetric splitters fabricated in three dimensional geometries for optical signal distribution with equal splitting ratios to various locations within the substrate is demonstrated here. The achieved axial symmetry with respect to the input waveguide can only be facilitated in a three dimensional geometry, and due to the high degree of symmetry an exceptionally even distribution of the output power for the different channels is expected. This demonstration provides an excellent example of femtosecond micromachined 3D structures that are very difficult to realize by other fabrication techniques.

Chapter 6 – This chapter will summarize all the results and provide some concluding remarks.
Chapter 2

Micromachining of Transparent Media

2.1 Introduction

Laser micromachining using femtosecond pulses is a powerful and versatile technique for fabricating photonic devices in transparent materials. It enables high-density photonic structures since multiple layers of waveguides can be fabricated on a single substrate and, more importantly, opens the door to a wide range of new devices fabricated in three dimensional geometries, many of which providing enhanced functionality not possible in planar geometries. Since the micromachining process is very versatile and allows for rapid fabrication of a wide range of structures under computer control, phonic devices can be designed, fabricated, and tested rapidly, thereby streamlining the entire development process. This chapter will start by briefly discussing the physical process of laser induced material modification. It will then give a quick overview of the development of the micromachining area from the initial demonstrations
to the most current devices. This will be followed with a discussion of the machining laser sources and the two modes of operation that are currently used, and the chapter will finally terminate with an overview of the work done by our group and a description of our micromachining setup.

2.2 The physical process

Transparent materials, such as glass, by definition transmit incident light without linear absorption. This is because they have band gaps of several electron volts which cannot be bridged by typical light intensities. When a laser beam of sufficiently high intensity is focused into an optically transparent material, such as fused silica, at intensities higher than the self-focusing threshold, the intensity in the focal volume can become high enough to initiate nonlinear absorption and plasma formation leading to material modification [4 – 12]. Since this absorption is highly nonlinear, the permanent structural changes made are localized only to the focal volume, leaving the surround regions in the bulk and the surface of the substrate unchanged. Taking advantage of this process three-dimensional microstucturing of various photonic devices has been demonstrated in different materials. The high intensities required for micromachining are producible using mode-locked short pulse lasers. This is because these lasers spread the average power over discrete pulses widely spaced in time that therefore contain peak powers that can be in the mega Watt range. These laser sources for micromachining as well as the applications will be discussed in the following sections in greater detail.
Although there has been a great deal of literature discussing the applications of femtosecond machining and the operation of fabricated devices there has been comparatively little describing the actual physical process on a more than superficial level. Several research groups have investigated the process and continue to study it in greater detail. As is true of most research, with time a better understanding of the underlying mechanisms will certainly come to light. Although not yet completely understood, several ideas are commonly accepted and we will briefly review some of them here.

Recently *in situ* laser spectroscopy with a confocal microscopy-spectroscopy setup was used to carry out a very interesting study of the structural changes induced in fused silica glass (the material that we mostly work with in our group) after being exposed to focused femtosecond laser pulses [13]. Using an amplified femtosecond laser system fused-silica was machined at a range of pulse energies. The exposed and unexposed regions were then excited using a low power cw 488 nm argon-ion laser and the Raman and fluorescence spectra were measured. Fluorescence measurements provide information of the presence of optically active points in the substrate and Raman spectroscopy reveals the network structure. The acquired Raman and PL spectra after excitation were coupled into a spectrometer and analyzed using a nitrogen cooled CCD.

The results for the regions that were not exposed to the focused femtosecond pulses showed signals only due to the Raman scattering of the fused silica, fluorescence was not observed. The machined regions however, on top of the Raman scattering signals, also
showed with increasing machining pulse energy an increase in the intensity of a broad fluorescence band centered around 630 nm; the researchers conducting this study attributed this fluorescence to non-bridging oxygen hole centers [14] produced in the glass by the femtosecond radiation. To observe the changes in the Raman scattering spectra produced by machining more clearly this fluorescence signal was subtracted from the overall measured spectrum. What stood out in the normalized Raman spectra were two peaks at 490 and 605 cm\(^{-1}\) that increased in intensity with increasing machining pulse energy. These particular peaks are signatures of the breathing modes of the 3 and 4 membered rings in the silica network [15, 16]. It is known that an increase in density is produced by a decrease in the overall bond angle. The increase in these membered rings produced by femtosecond radiation leads to a decrease in the overall bond angle and therefore an increase in material density and index of refraction.

The changes in the Raman spectra signaling the increase in the membered rings and therefore the material density have also been observed in other experiments aiming to increase silica density. One group observed an increase in the Raman peaks in glass at 490 and 605 cm\(^{-1}\) with increasing fictive temperatures \((T_f)\). The increase in material density and refractive index of vitreous silica with increasing fictive temperatures is a well know fact [17]. Fictive temperatures increase with quicker cooling; the faster the quenching from high temperature melt the higher the fictive temperature [15]. Other experiments producing an increase in silica density, one using shock waves [18] and the other using neutron radiation [19], also observed changes in the Raman spectra similar to
what has been described above. All these results help reinforce the idea that femtosecond pulses focused into the bulk of silica glass dramatically increase the number of 3 and 4 membered rings in the silica network, which decreases the overall bond angle and results in an increase in the material density and index of refraction. This increase in the number of membered rings is signatured by a fluorescence band centered at 630 nm and peaks that increase with pulse energy at 490 and 605 cm⁻¹ in the normalized Raman scattering spectra excited from the machined regions.

All of this of course only occurs over a threshold pulse energy required to initiate the nonlinear absorption of incident light and subsequent modification of glass. For pulse energies just above this threshold the sample is only slightly modified, that is rearrangements of bonds take place but the overall glass structure is preserved, and the observed changes are “smooth” [13] with a small increase in material density and index. For even higher pulse energies relatively “rougher” structures are obtained this time with larger increases in the fictive temperature (Tₚ), material density, and index of refraction. The greater glass modifications observed in this case are believed to be formed by the generation of a plasma at the laser beam focus via multi-photon and avalanche ionization [20, 21], which through the transfer of energy to the material lattice leads to extremely high localized temperatures and pressures producing a shockwave (a “microexplosion”) resulting in an increase of glass density [5, 6].

Photo-ionization is basically the process of transferring an electron from the valence band to the conduction band. In the case of transparent materials this band gap to bridge
is quite large but high enough incident intensities can promote an electron across the band gap through a multi-photon absorption process – referred to as multi-photon ionization. Once in the conduction band the electrons (free carriers) can absorb energy linearly thereby allowing efficient transfer of energy from the incident field to them. As electrons continue to absorb incident energy their energy eventually increases well beyond the band gap and they become capable of promoting other valence electrons to the conduction band through impact ionization (a process where a high energy free carrier drops into the valence band and impacts another electron, promoting both itself and this other electron to the bottom of conduction band). The overall avalanching of electrons from the valence band to the conduction band by efficient energy absorbing free carriers that participate in impact ionization is know as avalanche ionization. Multi-photon ionization and avalanche ionization lead to the formation of a plasma. It is this plasma that is responsible for the transfer of energy to the material lattice and as the density of this plasma increases the amount of thermal energy and pressure being deposited into the focal volume also increases. Once the energy and pressure being deposited is enough to cause melting, a shockwave (a microexplosion) that modifies and permanently changes the material density takes place.

2.3 Micromachining background

This ability to increase the material density and index allows for the fabrication of waveguides embedded within the glass substrate and of course a multitude of optical
devices based on these elemental waveguides. The micromachining process using computer controlled stages allows for very rapid fabrication of a wide range of different devices. Multiple layers of waveguides can be fabricated on a single substrate thereby enabling high-density photonic structures. The greatest advantage of this versatile technique perhaps is the ability to rapidly create a wide range of new devices in three dimensional geometries, many of which providing enhanced functionality not possible in planar geometries.

Some of the first structures “micromachined” in fused silica were demonstrated in 1996 [9]. The light source used was an amplified femtosecond laser and device machining was accomplished by translating the glass substrate with respect to the incident laser beam using mechanical stages. Later that same year a method for three dimensional optical data storage inside transparent material was demonstrated [5]. A femtosecond laser was used to write bits of higher index on various planes within the substrate which could then later be readout. One year later in 1997, optical waveguides were demonstrated in other glasses including borosilicate, fluoride and chalcogenide glass [22]. In the years that followed the area exploded with considerable work being done. Many two dimensional photonic devices based on these elemental waveguides were demonstrated. In particular, X coupler and directional couplers were fabricated [8, 12, 23, 24], gratings were demonstrated [25, 26], and interferometers were built [26, 27].

In recent years there have been some exciting applications of femtosecond machining. For example, many new materials have been explored. Micromachining was
demonstrated in Ti:Sapphire crystal using an amplified laser [28]. Machining in this case was a double-two-photon process and the modified regions showed a decrease in material index. A simple two dimensional splitter was also demonstrated in Lithium Niobate, a broadly used material for integrated optics [29]. Machining in active materials had also been achieved. Waveguide writing in Nd-doped glass produced active waveguides with a peak gain of 1.5 dB/cm at 1054 nm [30] and in Er:Yb-doped glass produced active waveguides with gain over the entire C band and with a peak gain of 1.4 dB/cm at 1530 nm [31, 32]. There has also been a lot work with photosensitive materials such as polymethyl methacrylate (PMMA). After multiphoton absorption the exposed region changes in properties and can be selectively etched away leaving behind the designed structure. This has been used to create holographic gratings [33] and three dimensional

![Figure 1](image-url)  
**Figure 1:** SEM image of a photonic crystal structure fabricated in multifunctional inorganic-organic hybrid polymer using 2 photon polymerization produced by a Ti:Sapphire femtosecond laser. Ref [34].
photonic crystal structures [34], such as the one shown in figure 1, among many other micro-devices [35 – 38]. Our group has done some of the most interesting work to date on the development 3D photonic devices in glass; many of these will be described in the following sections.

2.4 Laser sources and modes of operation

Many of the devices discussed in the previous section were fabricated using amplified femtosecond laser systems. Amplified systems are attractive and are widely used because they can provide high pulse energies (μJ to mJ) for machining. However, because they are limited to relatively “low” repetition rates (few Hz to a few hundred kHz) their speed and versatility in fabricating optical devices is limited. Their complexity and cost has also increased interest in achieving higher-energy pulses using standard mode-locked lasers.

The pulse energies available from standard Ti:sapphire lasers is limited to several nanojoules. Machining with them requires focusing with very high numerical aperture objectives in order to reach intensities sufficient to initiate the nonlinear absorption process. These requirements impose very severe constraints on the substrate depths that can be machined and in general make everything very difficult to work with. For micromachining and many other nonlinear experiments considerable more pulse energy is required. Cavity dumping has produced pulses as high as 100 nJ with pulse durations of 50 fs, and 40 nJ with pulse durations of 13 fs [41, 42]. However, just as with
amplified systems this technique is complex and expensive. Ideally, simpler and more cost effective methods are desired. One approach is to extend the length of a standard femtosecond oscillator cavity, leading to a reduced pulse repetition rate and, for a given average power, higher output pulse energies. Using a 1:1 telescope to extend the cavity length, 36 nJ pulses at 15.5 MHz have been produced [43]. Using a similar setup, 24 nJ pulses at 30 MHz with sub 10 fs durations were also obtained [44].

Our group has recently demonstrated high energy pulse generation using Herriott-type multiple-pass cavities (MPCs). MPCs allow for the scaling of output pulse energies by extending the laser cavity length and lowering the pulse repetition rate in a well controlled and compact fashion [45]. We have also recently developed an analytical set of guidelines for MPC design that can be used to construct a wide range of lasers using MPCs [46]. Using an MPC to reduce the laser repetition rate to 15 MHz, we have demonstrated 11.5 nJ pulses with 16.5 fs duration [45]. We further reduced the repetition rate to 4 MHz using an additional saturable Bragg reflector to stabilize the laser performance and suppress multiple pulsing [47]. This laser yielded 48 nJ with 55 fs durations when operated with small net negative intracavity group-delay dispersion (GDD). Operated with a small net positive GDD it produced maximum pulse energies of 90 nJ with 80 fs durations. These pulses were chirped however and required external compression.

Some of the highest pulse energies available directly from a laser oscillator were only recently achieved. Our group demonstrated a high-pulse energy Ti:sapphire laser
oscillator capable of producing 150 nJ pulses, which is approximately an order of magnitude greater than standard lasers. The output nearly transform-limited pulse duration was 43 fs at a repetition rate of 5.85 MHz, yielding peak pulse powers of 3.5 MW [48]. The output bandwidth was 16.5 nm corresponding to a 39 fs transform-limited pulse duration. Pumping at 9.4 W, 877 mW of average output power was obtained. To achieve these results an MPC that extended the unfolded cavity length from 3 m to 51 m was used. This was done in a very compact fashion so that the overall system length was still ~1 m. In order to balance the self phase modulation (SPM) produced at these high intensities, specially designed double-chirped mirrors (DCMs) were used to operate this laser with a net negative intracavity dispersion. DCMs provide a very controlled method for managing intracavity dispersion over broad bandwidth ranges [49, 50], which is critical to the performance of short pulse laser systems. They can be used with a wide range of gain media and allow for prism-less cavity designs.

Very recently 220 nJ, 30 fs pulses at a repetition rate of 11 MHz were demonstrated using an MPC based Ti:Sapphire oscillator. This laser operated with a net positive GDD and required external compression using a prism compressor of the chirped picosecond pulses that it produced [51]. Fine tuning of the cavity GDD was done using another prism pair. It was found to be difficult to start Kerr-lens mode-locking in the regime of positive GDD so the prisms were set to produce a negative cavity GDD to initiate startup. Once started the prisms were adjusted for optimal performance in the positive dispersion regime. Here highly stable single pulse operation was achieved and pumping at 10.2 W
Chapter 2: Micromachining of Transparent Media

yielded approximately 2 W of average output power. Pulse energies of 180 nJ and 30 fs duration were obtained after compression. With additional optimization of the cavity GDD and pump power 26 fs pulses were obtained, but the pulse energy and average power had to be reduced to 130 nJ and ~1.5 W, respectively. The output bandwidth obtained was 60 nm, corresponding to 11 fs transform limited pulses. Thus, even the shortest pulses obtained were a factor of 2.36 away from their transform limit due to higher-order spectral phase at the edges of the spectrum. It was observed that in this region of positive GDD there was a region where it was possible to obtain reproducible modulation of the pulse energy at half the repetition rate of the laser, with the energy of every other pulse reaching a peak of 220 nJ.

Ultralow repetition rate lasers have also been designed using MPCs. Stable operation at 1.2 MHz repetition rate was demonstrated in a mode-locked Nd:YVO₄ laser using a semiconductor saturable-absorber mirror (SESAM) [52]. The configuration of this laser’s MPC was similar to the Herriott-type MPC but folded in two using two plane mirrors, and it increased the cavity length to ~ 125 m. Pumped with a fiber-coupled laser diode at 15 W, 470 mW of average output power was obtained. This laser produced very high energy 392 nJ pulses with 16.3 ps duration and 24 kW peak power. The output power was seriously limited by losses at the MPC mirrors. With fewer passes through the MPC and operating at a repetition rate of 2.3 MHz the average output power was improved to 2.5 W. Operation at sub-1 MHz repetition rates was limited by increased nonlinearities causing pulse breakup. Although the pulses produced by this laser were
quite long (ps versus fs) this laser demonstrates record pulse energies from an oscillator using an MPC. It also demonstrates the scalability of MPC designs and the ability to generate very low repetition rates. At these low repetition rates however, proper care must be taken to limit MPC losses.

For micromachining femtosecond laser sources are required; although the ultralow threshold laser provided incredibly high pulse energies it’s pulses were quite long (ps versus fs). In the femtosecond range the Krausz laser oscillator \cite{51} produced the highest pulse energies to date. This laser however required tuning of prism pairs to bring the cavity dispersion from a negative GDD to a positive GDD for startup. More importantly, it required external compression to bring it’s ps pulses down to fs pulses. In terms of the best performance directly from the oscillator without requiring any cavity adjustments or external compression of any kind the laser developed by our group generating 150 nJ pulses at 5.85 MHz is optimal. This is the laser we are currently using for micromachining in our group and it’s layout is given in figure 2.

Note that none of these extended cavity lasers however are capable of producing the μJ to mJ pulse energies provided by amplified systems. Their advantage however, apart from being simpler and cheaper to build, is the high repetition rate they operate at compared to amplified systems (MHz versus kHz). The time scale for heat diffusion out of the focal volume is on the order of ~ 1 μs \cite{53}. This is shorter than the time between successive pulses from kHz amplified lasers but longer than the time between successive pulses from MHz extended cavity lasers. As a result, machining by the extended cavity
oscillators is produced via a cumulative heating process whereby energy is deposited into the focal volume faster than it can diffuse away – rapidly increasing the temperature and melting the material. This enables device fabrication approximately three orders of magnitude faster than by amplified lasers (mm/s versus μm/s), which is a very significant advantage and provides considerable flexibility and versatility to the machining process.

![Figure 2: Schematic of the MPC Ti:Sapphire laser capable of generating record 150 nJ pulses at 5.85 MHz that we are currently using for micromachining in our lab. Ref [48].]

### 2.5 Research done by our group

While three dimensional couplers have been demonstrated with amplified femtosecond lasers [39, 40], oscillator machining has been limited to basic 3D waveguides, spaced over several tens of microns [24]. Using our high pulse energy laser oscillator [48] and its previous generations our group has fabricated waveguides and two dimensional optical devices including directional couplers, X couplers, and
interferometers [24, 27]. We have also demonstrated the ability to produce three-dimensional structures, which is one of the most attractive features of this fabrication technique. By changing the depth of the focal spot within the substrate, 3D waveguides were fabricated and next, by creating multi-layered 2D structures, the capacity to achieve high device densities was shown.

Beyond structural density, 3D fabrication allows for devices with functions and geometries that are not possible in two dimensions (planar geometries). As an initial example, we demonstrated a 1-to-4 waveguide coupler. Next, by combining a horizontally oriented X coupler with a vertically oriented directional coupler we demonstrated the ability to deliver different spectral components to different levels of the substrate. Recently we fabricated some of the most interesting and novel three dimensional devices, a 3D 3-waveguide symmetric directional coupler and a micro-ring resonator [54–56]. To our knowledge these were the first devices fabricated in three dimensional geometries using a femtosecond oscillator.

To further utilize the full potential of high energy laser oscillator based machining in transparent materials, we have most recently reported the demonstration of 1:N waveguide symmetric splitters fabricated in three dimensional geometries for optical signal distribution with equal splitting ratios to various locations within the substrate [57]. These splitters could be crucial for parallel distribution and cascaded devices. The achieved axial symmetry with respect to the input waveguide can only be facilitated in a three dimensional geometry, and due to the high degree of symmetry an exceptionally
even distribution of the output power for the different channels was achieved. These splitters will be discussed in more detail in chapter 5.

The machining laser has already been described earlier. Now a schematic of the machining setup is shown in figure 3. The femtosecond pulses are focused using a 100x, 0.8 NA Olympus microscope objective (which will be discussed in more detail in the next chapter) onto the machining platform. The platform consists of three Aerotech stages (only two are shown in the schematic). The x and y stages are the Aerotech ABL10050 (50 mm travel) and ABL10100 (100 mm travel), respectively. These are non-contact air bearing stages that are guided using magnetic fields and are expected to provide ~ 2nm resolution. And the vertical z stage is the Aerotech ANT 4V (4 mm travel), which by way of an amplified linear encoder can provide a similar resolution.

![Figure 3: Schematic of the micromachining setup. A microscope objective focuses the incoming femtosecond pulses into the bulk of the transparent sample and photonic structures are fabricated by translating the sample with respect to the incident beam (there are three translation axis x, y, and z – only two are shown here). On the right is one of the first structures fabricated with the new stages: a 100 μm radius ring written at a rapid speed of 10 mm/s illustrating the impressive performance of these stages (as well as their tuning), and the overall machining setup.](image-url)
These stages sit on 4 inch thick block of granite that is specified to be flat to 100 millionths of an inch, providing exceptional flatness but also great stability. The entire setup is controlled via firewire and computer software. Setting the PID controller gains for all the stages is very time consuming but critical to their performance. Once they have been set correctly G code is written to command the stages to draw the desired pattern. The G codes for most of the devices discussed in this thesis are included in the appendix. Also shown in figure 3 is one of the first structures fabricated with the new stages: a 100 $\mu$m radius ring written at a rapid speed of 10 mm/s, illustrating the impressive performance of these stages (as well as their tuning), and the overall machining setup.
Chapter 3

Straight and Curved Waveguide Characteristics

3.1 Introduction

Curved and straight waveguides are the fundamental building blocks of most photonic devices. The focus of this chapter is to characterize these structures. It will begin by first looking at the machining setup parameters that are used; these will be the same for all the machined structures presented in this thesis. Then the propagation losses of straight waveguides will be evaluated. The effect of multiple re-writing and their propagation losses will also be studied. With a much better understanding of the linear losses, the next effect to study will be the bending losses. In particular, 90° circularly curved waveguides of various radii will be fabricated and their losses estimated. The
observed losses will be compared to the estimated losses calculated by computer using guided mode analysis. Since these types of waveguides are the building blocks of many practical devices a proper understanding of the loss per unit length, per unit bend angle, as well as per re-trace (re-write) of the waveguides will provide a useful structured set of guidelines for future device fabrication using our particular setup. It may also possibly reveal some of its limitations.

3.2 Machining parameters and setup details

For all of the machining studies reported in this thesis the substrate material used was a transparent silica glass, in particular Corning 0215 soda lime glass. This substrate was chosen because it was widely available in the form of microscope slides and very cheap (approximately $0.33 per slide). It also exhibited an increase in material density and index after melting by femtosecond pulses, which produced the waveguiding properties that we desired. With other substrate materials it is also possible obtain a decrease in material density after machining [58, 59]. In this case a compression ring of higher density is created in between the machined region that has expanded and the surrounding region, whose density has remained unchanged. Waveguiding has been demonstrated in this compression region in the form of tubular waveguides [59].

The material composition and physical properties of the Corning 0215 glass used are shown in tables 1 and 2. The SiO$_2$ concentration is 73% and the rest of the substrate is composed of various metals impurities.
Chapter 3: Straight and Curved Waveguide Characteristics

Table 1: Chemical composition of Corning 0215 glass

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO₂</th>
<th>Na₂O</th>
<th>CaO</th>
<th>MgO</th>
<th>Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>% composition</td>
<td>73</td>
<td>14</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2: Physical properties of Corning 0215 glass

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coeff. Of Exp.</td>
<td>$89 \times 10^{-7}$ cm/cm/°C</td>
</tr>
<tr>
<td>Strain Point</td>
<td>511 °C</td>
</tr>
<tr>
<td>Anneal Point</td>
<td>545 °C</td>
</tr>
<tr>
<td>Soften Point</td>
<td>724 °C</td>
</tr>
<tr>
<td>Density</td>
<td>2.40 g/cm³</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.515 @ Sodium D Line</td>
</tr>
</tbody>
</table>

A transmittance plot for a ~ 1 mm thick sample of this substrate is shown in figure 3. Note that significant absorption occurs below 280 nm. In our case we are machining with a mode-locked Ti:Sapphire laser whose mean wavelength is 790 nm, indicating that initiation of machining is at least a three photon process, certainly not less.

We had also considered what would have happened had we tried using a substrate with a greater SiO₂ purity, for example the Corning Vycor Brand 7913 glass, whose SiO₂ concentration is 96.4 %. The transmittance plot for this substrate is shown in figure 5. Note that the lower metal impurity concentration in this glass leads to shift in the absorption band to lower wavelengths. For this material significant absorption occurs only below 210 nm. Thus, although the lower metal impurity concentration may lead to lower scattering losses in the machined structures, initiation of the machining process is at least a four photon process making this material somewhat harder to machine than
Corning 0215 glass. The Vycor brand glass was also more than $25 per slide, approximately two orders of magnitude more expensive than a similarly sized Corning 0215 glass slide. For these reasons we did not pursue machining this material and focused mainly on working with Corning 0215 soda lime glass. The standard sample size used was a 75 × 38 × 1 mm microscope slide available from VWR.

As described earlier, machining was accomplished by focusing the femtosecond pulses using a 100x, 0.8 NA microscope objective that did not require oil immersion. Standard microscope objectives are specified to compensate for a certain cover glass thickness at which optimal focusing is achieved. The Olympus objective that we used was unique in that it offered the ability to adjust this cover glass compensation from 0.4 –

![Figure 4: Transmittance plot for ~1 mm thick sample of Corning 0215 soda lime glass. Ref [www.corning.com].](image-url)
1.1 mm, ideally thereby allowing us to focus and machine anywhere in this depth range. All adjustments were made by rotating the compensation collar on the shaft of the objective.

![Transmittance plot for ~ 1 mm thick Corning Vycor brand 7913 glass. Ref [www.corning.com].](image)

**Figure 5:** Transmittance plot for ~ 1 mm thick Corning Vycor brand 7913 glass. Ref [www.corning.com].

Before starting the machining experiments the threshold pulse energies required to initiate the machining process were approximated. The criterion used was observable white plasma formation during machining and substrate modifications visible to the eye under 40× magnification. Therefore, this was not the most robust of threshold studies but it provided numbers that should be very close to the actual threshold values. The plot of the observed threshold pulse energies for machining versus writing depth in the Corning 0215 glass substrate is shown in figure 6.
Machining beyond 1 mm although possible was not tested because the glass substrates were all only 1 mm thick; also compensation for thicknesses below ~0.38 mm was not available with our objective. The threshold pulse energy increases slightly over the range 0.38 to 0.95 mm but remains relatively flat indicating relatively good performance of the adjustable cover glass compensation offered by this objective. When the adjustment collar was fixed to a certain depth, machining with the same incident power was only possible in a ±40 μm range in the vertical (z) direction. Outside this range the beam diverged too greatly to focus tightly enough to initiate the machining process. This is the limitation of most standard microscope objectives that do not offer the ability to compensate for different depths, and illustrates the importance of this feature to be able to machine a various depths within the substrate.

![Plot of threshold pulse energy for machining versus the writing depth in Corning 0215 glass.](image)

**Figure 6:** Plot of threshold pulse energy for machining versus the writing depth in Corning 0215 glass.
Chapter 3: Straight and Curved Waveguide Characteristics

The machining parameters used for the studies discussed in this chapter are very similar to the parameters used by Andrew M. Kowalevicz, a recent graduate of our group, for his experiments [60]. This was done intentionally so that the results discussed in his PhD thesis could be used to compare to and complement the results that will be presented here. To machine the straight and curved waveguides ~ 88 mW was incident on the sample (~ 192 mW before the objective) so that the incident pulse energy was ~ 15 nJ at ~ 400 µm below the glass surface. In addition, the sample was translated in the writing direction at 10 mm/s at all times. These were conditions that Andrew had also used to conduct his studies.

3.3 Straight waveguides characteristics

The elemental building blocks of all photonic devices are waveguides and in particular straight waveguides. Here we were interested in determining the loss characteristics of these waveguides and more importantly the effect of multiple writing of the same structures.

Waveguide loss produces in an exponential decrease in the propagating optical power so that the power down the line at point 2 \( (P_2) \) is related to the power at an earlier point 1 \( (P_1) \) by

\[
P_2 = P_1 e^{-\alpha L} \quad \Rightarrow \quad \alpha = -\frac{1}{L} \ln\left(\frac{P_2}{P_1}\right).
\]

Here \( \alpha \) is the propagation loss in cm\(^{-1} \) and \( L \) is the propagation distance. The loss value is also often given in units of dB/cm, which can be obtained simply by taking \( 10 \log_{10}(\alpha) \).
There are two main sources of linear loss – absorption and scattering. Absorption is inherent to the wavelength dependent nature of the material we are working with. For Corning 0215 glass the transmittance, and therefore the absorption, can be estimated from the plot given in figure 4. Although we need to take advantage of this absorption to machine waveguides it also contributes to the attenuation of optical power traveling through them. Scattering on the other hand is caused by local inhomogeneities in the molecular structure of the glass and its index of refraction; it is also strongly wavelength dependent. Other sources of loss in straight waveguides are variations in waveguide geometry, such as micro-bends or core geometry/density changes, caused by errors in waveguide translation by the motorized stages or fluctuations in the machining pulse energy.

To determine the straight waveguide loss four identical waveguides were machined using the machining parameters described earlier and were characterized using a cut-back loss measurement technique. A phase contrast microscope image of one of those waveguides is shown in figure 7. The waveguides were all separated by 100 μm to avoid

Figure 7: Phase contrast image of one of the straight waveguides written with 15 nJ of pulse energy at 10 mm/s, 400 μm below the surface.
any cross-talk and the machined waveguide diameters were \( \sim 2.68 \mu m \).

The main part of the test setup for this experiment is shown in figure 8. Mode-locked Ti:Sapphire light was launched in from the input end. Mode-locking was necessary to obtain interference free images and measurements, which were caused by the multiple reflections back and forth between the input and output end surfaces. The light sources used for testing were either the Femtolaser or the short cavity of the micromachining laser. They were fiber coupled to bring to the test setup and then coupled into the devices under test using free-space optics. Coupling was achieved using microscope objectives; for the 10x objective the focused spot size was \( \sim 3 \mu m \) on the input surface, and for the 20x objective it was \( \sim 1.6 \mu m \). Although the 20x objective provided better input coupling it also made it harder to find the input end of the devices because everything was that much bigger. Since the 10x objective provided acceptable

![Figure 8: Main part of the test setup for the straight waveguide loss study.](image-url)
coupling it was used for most of the studies. The outputs of each waveguide were collimated using another 10× objective and then apertured to obtain as close as possible just the power guided in the waveguide. This apertured signal was then measured using a sensitive Newport optical power meter. With the input and output powers catalogued, the glass sample was then cut approximately in half from 3.3 cm to 1.7 cm and all the measurements were repeated. In all cases the measured output power was maximized with careful iterative adjustment of the sample position with respect to the input beam. This took several minutes for each waveguide. Since the incident power remained the same and the coupling was optimized for each waveguide, it is approximated with good reason, that the light launched into each waveguide was identical. Given that, two waveguide lengths are sufficient to calculate the waveguide loss. This is understood first by considering the input-output power relation for a particular straight waveguide:

\[ O = s_2 (1 - s_i) e^{-\alpha L} I \]

Where \( I \) is the input power after the coupling objective at the input surface of the sample, \( O \) is the output power at the output surface of the sample, \((1 - s_i)\) is the fraction of the power lost at the input surface and \( s_2 \) is the fraction of the power lost at the output surface, \( \alpha \) is the linear propagation loss in cm\(^{-1}\), and \( L \) is the propagation distance. For two waveguide lengths with the same input powers \((I_1 = I_2)\) and with careful maximization of the output powers so that the coupling is optimized and approximately the same for all cases, we can combine the input-output power relations for the two
Chapter 3: Straight and Curved Waveguide Characteristics

lengths as follows:

\[ O_1 = s_2(1-s_1)e^{-aL_1} I_1 \quad \text{and} \quad O_2 = s_2(1-s_1)e^{-aL_2} I_2 = s_2(1-s_1)e^{-aL_2} I_1 \]

\[ \frac{O_2}{O_1} = e^{-a(L_2-L_1)} \]

\[ \alpha = \frac{1}{L_2-L_1} \ln \left( \frac{O_1}{O_2} \right) \]

where \( O_1 \) is the output of the waveguide of length \( L_1 \) and \( O_2 \) is the output of the same waveguide when cut down to length \( L_2 \), and \( \alpha \) is the propagation loss in \( \text{cm}^{-1} \).

Using this method the average linear loss for the straight waveguides was calculated to be \( \sim 1.54 \text{ dB/cm} \). This value is quite close to the value of 1.64 dB/cm found earlier this year by Andrew Kowalevicz [60] and the value of 1.6 dB/cm found also this year by another group [61]. Figure 9 shows a CCD image of the output intensity distribution of one of the straight waveguides. It is circularly symmetric and exhibits very good agreement with the fundamental Gaussian profile, suggesting singlemode operation.

Recall that total internal reflection occurs when light traveling in material 1 with index \( n_1 \) is incident on material 2 with index \( n_2 \) at an angle of incidence \( \phi > \arcsin(n_2 / n_1) \) (Snell's law). We take advantage of this effect to guide light in waveguides and photonic devices where waveguiding due to total internal reflection is produced by a positive \( \Delta n \) change between the core and cladding material. Just any type of waveguiding is not always sufficient, in most cases singlemode operation, that is propagation of only the lowest order (fundamental) mode, is necessary. Since different modes travel with
different speeds and can also interfere with each other leading both to spreading of the traveling optical pulses as well as noisy pulse intensity distributions, singlemode operation is desired for many applications such as optical communications.

![Image](image)

**Figure 9:** CCD intensity distribution of a straight waveguide showing a Gaussian shape and singlemode operation.

For the threshold values shown in figure 6 and the parameters used to fabricate the straight waveguides (15 nJ at 10 mm/s translation and 400 μm below the surface) singlemode waveguides were obtained. For larger pulse energies or lower translation speeds, producing the same fluence, the machined waveguides were larger in diameter and supported multimode operation. This was also exhibited in their output CCD intensity distributions that were no longer Gaussian in shape but had multiple peaks as shown in figure 10.

To estimate the change in index between the core and the cladding, Δn, for the straight waveguides V-number analysis can be used. This is not strictly correct because it assumes an index profile that is rectangular in shape; in our case we believe that the index
Chapter 3: Straight and Curved Waveguide Characteristics

Figure 10: CCD intensity distribution of a wide diameter waveguide showing multimode operation.

profile has the shape of an inverted bell. To confirm this we sent waveguide samples to Rinck Electronik located in Jena, Germany. They have developed an index profilometry system capable not only of measuring the index profile via reflection at the end facets but also from above for embedded structures up to 400 μm below the top surface. A first test scan of the index profile measured by Rinck for one of our waveguides is shown in figure 11. This measurement was done by shifting the focus of a laser beam along one of the end facets through a reference immersion liquid. The angle of the reflected beam is dependent on the refractive index at the point of focus and allows a reconstruction the index profile of the waveguide. This angle of reflection is also very dependent on the unevenness of the end surface and so to obtain a good profile a very high quality polished sample was provided to Rinck Electronik. The index profile shows an index contrast $\Delta n \sim 0.0035$, which is quite small. Unfortunately we were not able to get a final measurement from Rinck. They ignored my numerous calls and emails and never sent us
any updated data or returned our waveguide samples. Still this data shows the power of the commercial systems currently available for index profilometry. One other company that should be considered in the future for waveguide index profilometry is EXFO based in Quebec, Canada.

![Index Profilometry Diagram](image)

**Figure 11:** An initial test index profile of our waveguides obtained from Rinck Electronik.

As mentioned earlier, another simpler method to estimate the index contrast is V-number analysis. Again this assumes a rectangular index profile, which as we know is strictly speaking not correct but provides a helpful estimate. The waveguide diameter as shown in figure 7 is estimated to be ~ 2.68 μm. We had confirmed earlier after coupling laser light into very similar waveguides and observing the output modes that the singlemode wavelength cutoff was somewhere between 532 nm and 633 nm. This is a very coarse measurement and a result of a lack of tunable sources in this wavelength
range. In any case, the V-number is given by \( V = \frac{2\pi a NA}{\lambda_o} \), where \( 2a \) is the diameter of the waveguide, \( \lambda_o \) is the cutoff wavelength estimated to be in the range 532 – 633 nm, and NA is the numerical aperture given by \( NA = \sqrt{n_1^2 - n_2^2} \) with \( n_1 \) representing the refractive index of the core and \( n_2 \) representing the refractive index of the cladding. The fundamental mode will always propagate but the first higher order mode will start propagating at \( V = 2.405 \). Solving this for \( n_1 \) when \( n_2 \), the refractive index of the cladding material is known to be 1.515, gives the range for \( \Delta n \sim 0.0075 – 0.011 \). This is certainly larger than the estimate for the index contrast obtained from Rinck Electronik.

### 3.4 Multiple writing experiments and results

The linear loss for the straight waveguides was found to be \( \sim 1.54 \) dB/cm. The next question was, what is the effect of writing the same waveguide over itself multiple times? Will the multiple writing average or smoothen out the inhomogeneities of the written structure improving the texture of the core and it’s enclosing walls?

To test this four waveguides were written, each retraced twice, and their loss characteristics were measured using the same method used before: by measuring the power transmission, cutting the sample in half, and measuring the power transmission again. The ability to re-write the same structure is very powerful and depends heavily on the ability of the stages used to translate the sample to return exactly to the same starting position and travel the same path. Stability of the machining setup and machining laser
are also very important. A phase contrast image of the straight waveguides that were written twice is shown in figure 12. Notice that compared to the waveguide which was written only once (shown in figure 7) the waveguide diameter has increased to \(~ 2.97 \mu m\). Still when 800 nm laser light was coupled in the CCD output intensity distribution obtained was very similar to the one acquired for the singly written waveguides; it was circularly symmetric with a nearly Gaussian profile, suggesting singlemode operation.

The linear loss of these doubly written waveguides was obtained using the cutback loss measurement technique to be \(~ 1.05 \text{ dB/cm}\), an improvement of \(~ 0.5 \text{ dB/cm}\) over the singly written waveguides.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{doubly_written_waveguides.png}
\caption{Phase contrast image of the doubly written waveguides.}
\end{figure}

To see if this linear loss could be even further reduced, each of the waveguides were retraced twice more, that is written four times each. A phase contrast image of the four-times written guides is shown in figure 13. Notice this time that the waveguide diameter has again increased but only slightly compared to the doubly written waveguides.
Chapter 3: Straight and Curved Waveguide Characteristics

Figure 13: Phase contrast image of the four-times written waveguides.

The linear loss of these waveguides was also obtained using the same cutback loss measurement technique and found to be \( \sim 0.71 \text{ dB/cm} \), a further decrease in loss. Observation of the CCD output intensity distributions of these waveguides for 800 nm coupled light showed once again clear circularly symmetric near Gaussian distributions, suggesting singlemode operation. The diameters of the four-times written waveguides did not appear to be large enough to support the multimode behavior characteristic of large guides as shown in figure 10, at least not at 800 nm and for this measurement technique. This suggests that multiple writing can be used to fabricate straight waveguides with losses lower than those of singly written waveguides and that are still singlemode. The loss measurements are summarized in table 3 below.

Table 3: Loss characteristics for multiply written waveguides.

<table>
<thead>
<tr>
<th>No. of Writes</th>
<th>Linear Loss (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.54</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
</tr>
<tr>
<td>4</td>
<td>0.71</td>
</tr>
</tbody>
</table>
3.5 Curved waveguides characteristics

Along with straight waveguides the other elemental building blocks of most of photonic devices are curved waveguides. Here when we refer to curved waveguides we mean circularly curved waveguides that lie on a circle of fixed radius. For example, to fabricate the multi-port photonic device shown in figure 14, the directional coupler between ports $a$ and $b$ was fabricated using circular arcs to bring the straight waveguides close together in the interaction region $L$.

![Figure 14: Example of a multi-port photonic device we made using circular arcs. Ref [55].](image)

To study the loss characteristics of circularly curved waveguides, 90 degree circular arcs of radii ranging from 2 mm to 18 mm in steps of 2 mm were fabricated. A schematic of the machined structures is shown in figure 15. This schematic, which is not to scale, also shows the 5 mm straight waveguides that were machined at the beginning and end of the curved regions to couple light in and out of the curved waveguides. Figure 15 also shows phase contrast images of one of the curved structures; since the full image was acquired at 40× zoom it would not completely fit so only parts of the input, middle, and output regions are shown. For these devices to be machined correctly careful
consideration was taken in the writing the G-code controlling the stages to ensure velocity blending and smooth transition from the straight to the curved regions.

Figure 15: Schematic of the fabricated circularly curved waveguides showing the straight input and output waveguides as well as phase contrast microscope images of the different regions.

To test these devices 800 nm laser light was coupled in and the output intensity distributions were observed using a CCD camera. In all cases the observed output intensity was maximized with careful iterative adjustment of the sample position with respect to the input beam. This took several minutes for each structure. Since the incident power remained the same and the coupling was optimized for each case, it is approximated with good reason, that the light launched into each structure was identical. A picture of the test setup is shown in figure 16.

Since some of these curved waveguides occupied considerable space in the substrate it was critical to ensure that the substrate was as flat and as normal as possible with
respect to the writing beam, otherwise beam focusing errors would be produced and the written structures would not be uniformly written. This “leveling” of the writing surface was done using a goniometer as well as by eye, ensuring as much as possible that the amount of white light generation due to the plasma formation during machining was a uniform as possible. Of course perfect leveling was not possible and is not assumed here.

The test setup in this case was very similar to the free space coupling one that had worked very well for the straight waveguides. Andrew Kowalevicz had attempted a similar curved waveguide study for his PhD thesis but was not successful in obtaining any output signal from his curved structures. The study was attempted again for this Masters thesis and as expected, obtaining any output was extremely challenging. For the curved waveguide radii of 2 mm to 6 mm no output was observed even after considerable time and effort trying to optimize the (free space) coupling of the input light. Starting at 8 mm radius and above output signals were observable using the CCD camera. As a

![Figure 16: Part of the test setup for the curved waveguide loss study.](image)
function of increasing radii the bending loss in dB is approximately linearly decreasing (for a given index contrast $\Delta n$ between the core and the cladding). Therefore to find the linear fit only two points are required. To be sure three points were sought: the 90 degree bending loss values for 8 mm, 10 mm, and 12 mm radii curves.

Although the outputs of these structures were observable using the CCD camera, they were still too low in power to be properly measured using the available power meters. Extraneous light made it difficult to effectively single out the actual output signal. Thus, for this study the CCD camera was itself used as the power meter. To calibrate it, a signal of known power was attenuated heavily so as not to saturate the camera and the captured intensity distribution was catalogued. This reference was obtained by coupling the input laser light into one of the singly-written straight waveguides whose loss characteristics had been measured earlier. Since this straight waveguide was written and polished under the same conditions as the curved waveguides its properties were assumed to be the same as the curved waveguides. Also since the linear loss of this waveguide was now known and the output power for a given input had already been measured earlier, the coupling loss at the input and output surfaces given by $s_2(1-s_1)$ could be approximated and was found to be $\sim 11\%$. This coupling loss depends both on the index difference between the sample and the air as well as the quality of the polishing. Since these factors are assumed to be approximately the same for all the samples tested it was assumed that the coupling loss was the same for the curved waveguide structures as well. Given a reference for the CCD measurements, knowledge
of the coupling losses at the input and output surfaces of the curved structures, knowledge of the linear loss in the structures, and knowledge of the amount of power being coupled in – the output powers could now to be estimated using the captured CCD intensity distributions and with this information the bending losses can be approximated. After capturing the unsaturated CCD intensity distributions and subtracting the known coupling and linear losses the bending losses for the 8 mm, 10 mm, and 12 mm curved structures were estimated to be \( \sim 30 \text{ dB}, 23 \text{ dB}, \) and \( 17 \text{ dB} \) respectively.

To be able to compare these loss values to theoretical approximations Milos Popovic, a graduate student in the group, was consulted. Milos has written software that in addition to many other things also helps evaluate this problem. Briefly, in the software he has developed the bending loss is evaluated by numerically computing the complex propagation constant of the particular leaky mode of the circularly bent waveguide. The leaky mode field distribution and propagation constant are solutions of Maxwell's equations in cylindrical coordinates, cast as an eigenvalue problem where the eigenvector is the mode field and the eigenvalue is the propagation constant. The problem is formulated as a set of differential equations to solve for the transverse electric field component on the cross-section of the waveguide. The finite difference method is used to discretize the vector-field equations on the Yee grid, similarly to the finite-difference time-domain (FDTD) method. A finite-sized waveguide cross-section (computational domain) is used to carry out the computation. In addition, because these leaky modes lose power through radiation, an absorbing boundary condition is included to prevent this
radiation from reflecting off the artificial boundaries and affecting the solution. Perfectly-matched-layer (PML) boundary conditions, which may be viewed as a complex coordinate stretching, are applied in the mode solver near the boundaries to produce attenuation without spurious reflections. Please refer to his conference paper which describes his work in more detail [62].

Milos’ software can be used to approximate the bending losses for different waveguide geometries and index contrasts \( \Delta n \). For \( \Delta n = 0.005, 0.0075, \) and \( 0.01 \) the 90 degree bending losses for curved waveguides with circular cross-sections similar to ours are simulated for various radii in figure 17. Notice the linear decrease in loss that is characteristic of these structures.

![Figure 17](image_url)

**Figure 17:** Simulated 90 degree bending losses for curved waveguides with circular cross-sections (similar to ours) for various radii and index contrasts.
For the loss values estimated for my curved waveguides a linear fit is shown by the dotted line in figure 18. Also shown for reference are the loss lines for index contrasts $\Delta n = 0.005$ and 0.006. From the figure the linear fit appears to indicate the index contrast for my structures to be $\Delta n \sim 0.0057$.

![Graph showing simulated 90 degree bending losses for curved waveguides with index contrasts $\Delta n = 0.005$ and $\Delta n = 0.006$.](image)

**Figure 18**: Simulated 90 degree bending losses for curved waveguides with index contrasts $\Delta n = 0.005$ and $0.006$ given by the solid lines. The linear fit to the loss values estimated for my structures is given by the dotted line.

Although Andrew was not able to complete a similar curved waveguide loss study he was able to estimate the bending loss indirectly with the fabrication of the ring resonator shown in figure 19. For a broadband input the output obtained is sinusoidal in shape.
tracing out a fringe pattern; this results from the fixed circumference of the ring allowing only certain wavelengths to fit constructively. The fringe pattern can be used to estimate the loss in the ring and then with the aid of Milos’ software estimate the index contrast. Using this method Andrew estimated the index contrast to be in the range $\Delta n \sim 0.01 - 0.015$. This is almost double the index contrast value found in this thesis.

So the question is, what is the reason for this difference? Of course, there are two possible explanations:

1. The index contrast value found here is not correct due to the following possible errors
   - Fabrication errors – not actually machining with the specifications that were assumed (incorrect pulse energy, etc.).
   - Measurement errors – the calibration of the CCD was not correct, the CCD was auto-gaining even though no such option appeared to be available for this model (it was off), the attenuators that were used to attenuate the large signal during referencing were not attenuating to specifications, the estimated coupling losses are not correct, the different samples (straight versus curved) although machined and polished under the same conditions are still sufficiently different enough to lead to calculation errors.

2. The index contrast value found in this thesis is actually correct and there was an error in Andrew’s measurement, or his bends were machined differently
leading to different index changes. Also, since the ring is not actually a true ring — there are input and output waveguides branching in and out of the structure as well as intersecting at one point as shown in figure 19 — it is not clear how valid the loss value he obtained really is.

These are some of the possible reasons for the discrepancy; of course there can be other less obvious reasons as well. To be sure this study should be repeated but under different conditions. Part of the reason that Andrew was not successful in his direct study and repeating the study here was found to be extremely challenging is the design of the test setup. The way it is currently designed and the use of free space coupling makes measurement taking in this case prohibitively difficult. A complete redesign is recommended, this time with the use of direct fiber butt coupling into and out of the machined sample with the use of index matching liquid. This of course has it's own problems such as, how do you find the input and output? But these problems can be overcome with the purchase of extra tools specially designed for this application. Also the

\[ R = 1.0 \]

\[ L = 0.5 \text{ mm} \]

\[ 100 \mu\text{m} \]

**Figure 19:** Schematic of a ring resonator. Ref [56].
machining of large markers in the sample can make it easier to locate the input and output ports. A visiting scientist in our group Kenya Suzuki is currently working on addressing this very problem and is in the process of designing a suitable test setup. He obtained encouraging results in his initial trials.
Chapter 4

Broadband Characterization of X and Directional Couplers

4.1 Introduction

Using the elemental straight and curved waveguides discussed in the previous chapter most two dimensional and three dimensional photonic devices can be built. Two very important two dimensional devices are the directional coupler and the X coupler, both of which are very useful for optical signal distribution to various locations and devices. This chapter will focus on the broadband characterization of the directional and X couplers fabricated by our group and specify some of the conditions under which they perform their best.
4.2 Directional coupler design and characterization

A schematic of a directional coupler is shown in figure 20. For light launched into a waveguide although most of the electrical field is guided in the waveguide core the exponentially decreasing evanescent tails propagate in the cladding. If we have two waveguides that are sufficiently close together, such as in the interaction region of the directional coupler, and light is coupled into the first waveguide it is possible for the evanescent field traveling in the cladding to be coupled into the core of the second waveguide. This coupling of light from waveguide to waveguide is described by coupled-mode theory [63 – 65].

For the two waveguide structures in figure 20 oriented and aligned in the z direction assume that they are separated by distance \(d\) in the interaction region of length \(L\). For waveguides that are lossless with uniform properties the ratio of the power at the output of waveguide two \((P_{\text{out2}})\) to the power coupled into waveguide one \((P_{\text{in1}})\) is known as the coupling ratio and can be written as

\[
CR = \frac{P_{\text{out2}}}{P_{\text{in1}}} = \frac{P_2(z = L)}{P_1(z = 0)} = \frac{\kappa_{12}^2}{\gamma^2} (\sin \gamma L)^2
\]

where \(\kappa_{12}\) is the coupling coefficient and \(\gamma\) is a function of the propagation constants of the two waveguides \(\beta_1\) and \(\beta_2\) described by

\[
\gamma^2 = \kappa_{12}^2 + \left(\frac{\beta_1 - \beta_2}{2}\right)^2.
\]

When the two waveguides have identical propagation constants then
\[ \gamma = \kappa_{12} \propto \frac{1}{\beta_2} \int_{-\infty}^{\infty} u_1(y)u_2(y)dy. \]

where \( u_1 \) and \( u_2 \) are the eigenmodes of propagation in waveguide 1 and waveguide 2 respectively. Notice that the coupling ratio \( CR \) is sinusoidal in \( \gamma \) and the interaction length \( L \). For every length \( L = 2\pi/\gamma \) the coupling coefficient goes through one complete oscillation, that is power is coupled completely from waveguide 1 to waveguide 2 and then coupled completely back to waveguide 1. For half this length, known as the characteristic length \( L = \pi/\gamma \), complete coupling of power is obtained between waveguides 1 and 2. As \( L \) increases the coupling ratio undergoes more oscillations. On the other hand as the separation between the waveguides \( d \) is increased, the overlap of the evanescent field in the cladding with the core of the adjacent waveguide decreases and so does the coupling ratio. This is manifested by a slower power oscillation, that is an increase in the periodicity of the coupling ratio \( CR \).

Single wavelength characterization of micromachined directional couplers has been conducted by Andrew Kowalevicz (a former graduate student) and Kaoru Minoshima (a

![Figure 20: Schematic of a directional coupler.](image_url)
former postdoctoral associate) in our group. They machined a series of directional
couplers with different waveguide spacings \( d \) and interaction lengths \( L \) and characterized
their performance. They observed the sinusoidal nature predicted by couple-mode theory
and confirmed proper operation of these photonic devices. At the time this was the first
demonstration of its kind for micromachined devices [27, 66].

The previous work on directional couplers was based on single wavelength
characterization and here we plan to look at the broadband performance of these devices
hoping to reveal some guidelines for future designs. Also since the coupling is
wavelength dependent (through the propagation constant \( \beta \)) coupled-mode behavior can
be confirmed directly through broadband characterization. This work was a collaborative
effort with Andrew for this thesis. After the devices were machined, we acquired the
data, and finally cleaned up and formatted all the data and wrote the computer programs
necessary to analyze the device performance and extract the particular device features.

For this study eight directional couplers were built with designs similar to the
schematic shown in figure 20. They were fabricated under the same machining
conditions used in the previous chapter (15 nJ pulses at 5.85 MHz at 10 mm/s). The
bends into the interaction region were based on circular arcs on a circle of 10 mm radius.
The waveguide spacing \( d \) was fixed to 5 \( \mu \)m and two couplers for each interaction length
\( L = 1.0 \) mm, 1.5 mm, 2.0 mm, and 2.5 mm were fabricated. The broadband light source
used to test these devices was a mode-locked Ti:Sapphire laser and the output light was
captured using a spectrometer.
Chapter 4: Broadband Characterization of X and Directional Couplers

To evaluate the wavelength dependent performance of the directional couplers two transfer functions were sought: the “through” transfer function between the output and input of the same waveguide and the “cross” transfer function between the output of the second waveguide and the input of the first waveguide (and vice-versa). To begin, the through and cross spectrums needed to be obtained and compared to the input or reference spectrum for each directional coupler. As an example, for the \( L = 1.5 \) mm device, these spectrums are shown in figure 21.

The input spectrum from the mode-locked laser is given by the solid line. The through spectrum, which is the average of the two through spectrums (from Input1 to

![Figure 21: Spectrum for the \( L = 1.5 \) mm directional coupler showing the through, cross, and their sum compared to the input (reference) spectrum.](image-url)
Output1 and Input2 to Output2), is given by the circle (o) curve. And the cross spectrum, again the average of the two cross spectrums (Input1 to Output2 and Input2 to Output1), is given by the cross (x) curve. Notice the difference in the shape of the cross and through spectrums indicating the wavelength dependent nature of the coupling coefficient. The sum of these two spectrums produce the “summed output” spectrum which is very close in shape to the input (reference) spectrum as is required and expected.

Now to observe the wavelength dependent coupling more clearly the cross and through transfer functions were calculated by dividing the normalized cross and through spectrums with the reference input spectrum for each interaction length $L$. The transfer function plots for $L = 1.0$ mm and $1.5$ mm are given in figure 22. Notice that for $L = 1.0$ mm the interaction length is not long enough for appreciable coupling to occur and most of the power coupled into the through port remains in the through channel (solid line). Some power however is coupled into the cross channel (dashed line). As the interaction

![Figure 22: Cross and through transfer functions for $L = 1.0$ mm and $1.5$ mm directional couplers.](image)
length is increased to $L = 1.5 \text{ mm}$ so does the coupling and we observe more power in the cross channel (dashed line) compared to the through channel (solid line).

As the interaction lengths are increased even further to $L = 2.0 \text{ mm}$ and $L = 2.5 \text{ mm}$ the coupling also increases as is shown in figure 23 but it’s wavelength dependent nature also becomes more apparent: the shorter wavelengths are transferred more strongly then the longer wavelengths. For $L = 2.5 \text{ mm}$ almost complete coupling of wavelengths below 760 nm occurs and it is expected that for even longer interaction lengths we would observe the coupling of these short wavelengths from the cross port back to the through port again. This broadband experiment, different from the single wavelength experiments conducted earlier, helps confirm again the operation of these directional couplers but more interestingly gives us the transfer functions of these directional couplers and how they evolve for increasing interaction lengths thereby allowing us to
predict beforehand the coupling to expect for any particular wavelength in our band of operation.

4.3 X coupler design and characterization

A schematic of the X couplers that were machined is given in figure 24 below. Note that it is based on the crossing of two single mode waveguides at an angle $\theta$ in the form of an X with one input port and two output ports. The aim of this design is to have better wavelength independent coupling to both output ports. This would be an advantage over the directional coupler, which due to the wavelength dependent coupling coefficient is quite wavelength sensitive and cannot serve as a proper broadband power coupler. This design for a broadband coupler as it stands is not optimal, a better design for a true "splitter" will be presented in the following chapter.

To demonstrate the operation of the X couplers several were fabricated with different crossing angles $\theta$ and, once again as in the previous study, the cross and through transfer functions were sought. In this case, the through transfer function would be the ratio of Output1 and the Input, and the cross transfer function would be the ratio of Output2 and

\[ \frac{\text{Output1}}{\text{Input}} \]

\[ \frac{\text{Output2}}{\text{Input}} \]

Figure 24: Schematic of an X coupler.
the Input. To characterize the broadband performance a mode-locked Ti:Sapphire laser was used as the input source and the output was measured using a spectrometer. To begin, the through and cross spectrums needed to be obtained and compared to the input or reference spectrum for each X coupler. As an example, for an X coupler with crossing angle $\theta = 1.25^\circ$, these spectrums are shown in figure 25.

The input spectrum from the mode-locked laser is given by the solid line. The through spectrum from the Input to Output1 is given by the circle (o) curve. And the cross spectrum from the Input to Output2 is given by the cross (x) curve. Notice that unlike the directional couplers discussed in the previous section the

![Figure 25: Spectrum for the $\theta = 1.25^\circ$ X coupler showing the through, cross, and their sum compared to the input (reference) spectrum.](image-url)
cross and through spectrums here are very similar in shape indicating the wavelength independent performance desired of these couplers. The sum of these two spectrums produce the “summed output” spectrum which is very close in shape to the input (reference) spectrum as is required and expected.

Now to observe the broadband wavelength performance more clearly the cross and through transfer functions were calculated by dividing the normalized cross and through spectrums with the reference input spectrum for each crossing angle θ. The transfer function plots for θ = 1.0° and 1.25° are given in figure 26. Notice that for θ = 1.0° most of the power coupled into the device transfers to the cross channel (dashed line) while some power remains in the through channel (solid line). Now as the crossing angle is increased to θ = 1.25° we observe less power in the cross channel compared to the through channel. In both cases however the transfer functions exhibit a relatively flat response indicating almost wavelength independent performance over the entire range of

Figure 26: Cross and through transfer functions for θ = 1.0° and 1.25° X couplers.
Chapter 4: Broadband Characterization of X and Directional Couplers

operation. For an even larger crossing angle the transfer functions are plotted in figure 27. It shows a progression in the same direction – more power in the through channel and even less in the cross channel. In this case however, and for the even larger crossing angle samples we had fabricated, we observed slightly nonlinear wavelength performance – the devices no longer had strictly flat transfer functions. This may have been due to coupling between the waveguides or the geometry of the crossing junction for large crossing angles.

This experiment helps contrast the broadband performance of X couplers compared to directional couplers. As we had observed for $\theta = 1.0^\circ$ there is more power being coupled into the cross channel and for $\theta = 1.25^\circ$ there is more power remaining in the through channel. In both cases broadband flatness was obtained as desired. This shows that it is possible to tune the splitting ratio by adjusting the crossing angle all the while

![Figure 27: Cross and through transfer functions for $\theta = 1.5^\circ$ X coupler.](image_url)
preserving broadband operation. And a 50/50 splitting ratio should be attainable at some crossing angle between $\theta = 1.0^\circ$ and $\theta = 1.25^\circ$. The design of these broadband "splitters" was not optimal in that they required the actual crossing of two straight waveguides with part of one them just hanging there (as shown in figure 24). A more elegant design with the aid of better machining stages is presented in the next chapter.
Chapter 5

1:N Waveguide Splitters

5.1 Introduction

Recent work on photonic device fabrication in transparent materials using femtosecond pulses has enabled the creation of a wide variety of devices. Because the material modification is initiated by a nonlinear interaction, structures can be created at various depths within the substrate. Two dimensional devices such as X and directional couplers [8, 12, 23, 24], gratings [25, 26], and interferometers [26, 27] as well as active waveguides [30 - 32] have been demonstrated. While three dimensional couplers have been demonstrated with amplified femtosecond lasers [39, 40], oscillator machining has been limited to basic 3D waveguides, spaced over several tens of microns [24]. Our group has recently demonstrated novel 3D devices fabricated by oscillator machining
including a 3-waveguide symmetric directional coupler and a micro-ring resonator [54 – 56]. To further utilize the full potential of high repetition rate laser oscillator based machining in transparent materials, the demonstration of 1:N waveguide symmetric splitters fabricated in three dimensional geometries for optical signal distribution with equal splitting ratios to various locations within the substrate is reported here. These splitters could be crucial for parallel distribution and cascaded devices. The achieved axial symmetry with respect to the input waveguide can only be facilitated in a three dimensional geometry, and due to the high degree of symmetry an exceptionally even distribution of the output power for the different channels can be expected. Femtosecond micromachining provides a simple method for the high speed fabrication of such three dimensional structures, some of which are very difficult to produce by other fabrication techniques.

5.2 Experimental description and results

These devices represent a more elegant version of the X couplers presented in the previous chapter that were based on the crossing of straight waveguides; recall the X couplers did not have a common input port and had sections of their waveguides hanging and serving no purpose. A schematic of the splitters fabricated for this experiment are shown in figure 28. These devices have output ports branching out of a common input channel and their design relies on the ability of the machining stages to be able to correctly re-trace the common input path.
The splitters were fabricated using the same 100x, 0.8 NA microscope objective used for the straight and curved waveguide study. In this case 18 nJ pulses were used to machine the structures in the Corning 0215 substrate at 10 mm/s. For the first time all three axis of the computer controlled stages capable of providing 2 nm resolution were used. As always the glass substrates were cut and polished after machining to provide access to the input and output ports for device characterization and analysis.

Figure 28 shows the schematic of the representative devices that were fabricated for this 1:N waveguide splitter study. The 1:2 Y splitter is shown in figure 28 (a) with the input and output ports in the same plane and with 180 degree symmetry. The 1:3 splitter shown in figure 28 (b) is the analog of the Y splitter with three-fold symmetry and forms an equilateral triangle at the output. The 1:4 splitter with four fold symmetry shown in figure 28 (c) forms a square at the output. Notice that in all cases the common input channel is designed to lie in the center plane so that all output channels are displaced in the vertical (z) direction from the input by the same amount. The input waveguide in all cased was 5 mm in length leading to the splitting region spanning 10 mm in the axial (x) direction with a splitting angle of ~ 0.12 degrees for the Y splitter and ~ 0.16 degrees for

![Figure 28](image)

**Figure 28:** Schematic of the symmetric 1:2 (a), 1:3 (b), and 1:4 (c) waveguide splitters fabricated in 3D using our femtosecond oscillator.
the 1:3 and 1:4 splitters, and finally terminating with the output waveguides also 5 mm in length.

Figure 29 shows phase contrast microscopic images of the input waveguide (a), splitting region (b), and output waveguides (c) of the 1:2 splitter. The waveguides were 2.8 μm in diameter and the splitter was written by retracing the input waveguide twice. Notice from the form of the splitting region shown in figure 29 (b) that in the plane of the substrate the left waveguide was written before the right one and so what we see mostly is the overlap of this right waveguide. The two output channels were designed to be 40 μm apart; this separation was sufficient to avoid any cross coupling. The phase contrast images for the 1:3 and 1:4 splitters looked very similar to the ones presented here for the 1:2 splitter. The form of the input waveguide, output waveguides, and splitting regions looked exactly the same as they should. The only observable difference was the diameter

![Image of phase contrast microscopic images](image)

**Figure 29:** Phase contrast microscopic images of the input waveguide (a), splitting region (b), and output waveguides (c) of the 1:2 splitter. In the plane of laser writing the left waveguide was written before the right waveguide as is observed in the overlap of the waveguides before splitting shown in (b).
of the common input waveguide, which increased in diameter as it was re-written three times in the case of the 1:3 splitter and four times in the case of the 1:4 splitter. This lead to multimode behavior in the case of the 1:4 splitter as will be shown later.

Notice for a moment shape of the input waveguide, which remained the same for all cases. It is only a few microns in diameter and has been re-written by the femtosecond laser beam several times. Its smoothness and straightness illustrates the great performance of the air bearing stages used to translate the sample and just as importantly the excellent stability of the designed machining setup as well as the quality of the tuning performed on the controlling PID parameters for the stages.

For a quantitative spatially resolved characterization, a CCD camera was used to capture the unsaturated output intensity distribution. The acquired image for the 1:2 splitter is shown in figure 30 next to a CCD image of the output surface (with no output signal). An attempt was made to acquire an image of the end surface using our microscope setup with the sample standing up-right but it was very difficult to obtain anything useful.

![Figure 30: CCD image of the 1:2 splitter output surface and the corresponding CCD captured intensity distribution (unsaturated).](image)
The almost perfectly circular distributions suggest singlemode operation at the outputs of this Y splitter at 800 nm. The CCD captured images of the output surfaces as well as the unsaturated intensity output distributions at 800 nm for the 1:3 and 1:4 splitters are shown in figure 31 below. These splitters also exhibit almost perfectly circular output distributions suggesting singlemode operation of the output waveguides. Note that although the 1:3 and 1:4 splitters were specified to have symmetrically spaced outputs some form of stretching occurred in the z direction with the spacing in that axis scaled by a certain factor. It was later realized that the index difference between the air and glass, a factor of ~ 1.52, scaled the amount by which the laser focus was translated in the glass in the z direction as the z stage moved by a defined amount; this explains the ~ 60/40 scaling encountered in the z axis and can be overcome quite simply in the future by scaling all z axis translation instructions sent to the stages by the correct factor.

As mentioned earlier since the fabrication method used in these preliminary studies involved re-writing the input waveguides, their diameters were increased with multiple

![Figure 31: CCD images of the 1:3 and 1:4 splitter output surfaces and the corresponding CCD captured intensity distributions (unsaturated).](image)
Chapter 5: 1:N Waveguide Splitters

Figure 32: For the 1:2 splitter the light coupled from the left output port to the input is shown by (a) and from the right output to the input shown by (b). The intensity distribution shown in (c) is for light coupled from the output of the 1:4 splitter to the input. The multiple-peak distribution in this case indicates multimode operation of the input waveguide here as opposed to the singlemode operation observed for the 1:2 splitter.

writing. In order to test the mode structure of the common input waveguides, light was coupled into each output port and the intensity distribution at the input port was measured. For the 1:2 splitter and the 1:4 splitter these intensity distributions are shown in figure 32. As shown by figures 32 (a) and 32 (b), representing the coupling from the left output port to the input and right input port to the input port respectively, singlemode operation was confirmed in the input waveguide of the 1:2 splitter. In the case of the 1:4 splitter, clear multimode behavior was observed as shown by the multiple-peak distribution in figure 32 (c). Recall that during the waveguide loss study four-times writing did not lead to observable multimoding at 800 nm. This was because the waveguides were machined using 15 nJ pulses in that case compared to 18 nJ pulses here leading to somewhat larger diameter waveguides in this case. Of course singlemode behavior in the common input waveguide could ultimately be achieved in all cases by modulating the incident power of the writing beam over the input region.

Figure 33 shows the spatial power distributions of the outputs of the 1:4 splitter. The curves represent cross-sections of the intensity profiles of each port. These plots were used to calculate the splitting ratio over the four output ports, which was found to be
In a similar fashion the splitting ratios of the 1:2 and 1:3 splitters were calculated to be 50:50 and 32:37:31, respectively. These values demonstrate the remarkably equal distribution of the input signal over all the output channels. The small remaining deviations from optimal splitting could be due to small fabrication errors in the waveguides and their splitting angles, which will be overcome in the future.

This experiment has demonstrated the use of a high pulse energy, high repetition rate femtosecond laser, for 3D fabrication of photonic devices in glass. The fabrication of higher order (1:N) splitters was investigated via a characterization of three representative devices, a 1:2, 1:3, and 1:4 splitter. The results showed that three dimensional splitters with N fold axial symmetry can be designed to provide exceptionally even splitting ratios, a prerequisite for future optical signal distribution via parallel or cascaded assemblies of the demonstrated devices. This work was recently submitted to CLEO [57].

![Intensity profiles of 1:4 splitter outputs](image)

**Figure 33:** Cross-sections of the intensity profiles of each of the 1:4 splitter outputs. From left to right they correspond to the top-left output, bottom-left output, top-right output, and bottom right-output ports respectively.
Chapter 6

Summary and Conclusions

In this thesis we have explored the particularly interesting nonlinear application of laser micromachining. Focused high peak intensity pulses are capable of melting glass, which after re-solidification, experiences an increase in material density and index of refraction. We exploit this effect to fabricate waveguides and photonic devices capable of guiding light via total internal reflection. Femtosecond micromachining is very versatile and opens the door to a wide range of new devices fabricated in three dimensional geometries, many of which providing enhanced functionality not possible in planar geometries or producible by other fabrication techniques.

We began this thesis with a brief overview of the physical process of laser induced material modification, and looked at the historical development of the area from the initial demonstrations to the some of the most current devices. This followed with a
discussion of the types of machining laser sources currently used and an overview of the work done by our group, as well as a description of our micromachining setup.

The core of the thesis, which was the experimental results, was discussed next. The first issue addressed was the loss properties of curved and straight waveguides, the fundamental building blocks of most photonic devices. After outlining the machining setup parameters used to create these structures a comprehensive study of the linear loss properties of straight waveguides was done using the cutback measurement technique. For singly written waveguides the calculated loss value of ~ 1.54 dB/cm was exactly the same as those found earlier by two other researchers, providing confidence in our experiment. The question of whether multiple re-writing affects propagation losses was then addressed and we found indeed that multiple re-writing considerably improves waveguide loss to ~ 1.05 dB/cm for doubly written waveguides and 0.71 dB/cm for four-times written waveguides. With a better understanding of the linear losses, 90° circularly curved waveguides of various radii were fabricated and their losses estimated. After comparisons of these losses to estimations calculated using guided mode computer analysis the index contrast for our waveguides was estimated to be $\Delta n \sim 0.0057$, which seems quite reasonable. We also found that a re-design of the testing setup is in order, since taking measurements with the way it is currently designed is extremely challenging.

With a better understanding of straight and curved waveguide characteristics, more complex photonic devices based on these elemental structures were explored. We began by characterizing the broadband performance of the directional and X couplers fabricated
by our group. This not only helped demonstrate their proper operation, predicted by coupled mode theory, but also helped identify conditions under which they performed their best. These devices are of course very useful for optical signal distribution. Continuing along those lines we utilized the full potential of oscillator based machining in transparent materials to fabricate 1:N waveguide symmetric splitters in three dimensions for optical signal distribution; this was investigated via a characterization of three representative devices, a 1:2, 1:3, and 1:4 splitter. The results showed that three dimensional splitters with N fold axial symmetry can be designed to provide exceptionally even splitting ratios – 50:50 for the 1:2 splitter, 32:37:31 for the 1:3 splitter, and 26:25:27:22 for the 1:4 splitter. We believe that with further improvements these splitting ratios can be perfected, which will be very useful for future optical signal distribution via parallel or cascaded assemblies of the demonstrated devices.
Appendix – G Codes

Straight waveguide re-write study

; multiple write study
; setting to mm/sec
G76

; setting to absolute movements not relative
G90

; setting the feed rate to 10mm/sec
F10

; starting point in x and y axis
G1 X-20 Y-10

; pausing there for 5 seconds
G4 F5

; round #1 ---------------------------------------------------------------
G9 G1 X20
G9 G1 Y-9.8

G9 G1 X-20
G9 G1 Y-9.6

G9 G1 X20
G9 G1 Y-9.4

G9 G1 X-20
G9 G1 Y-9.2

; round #2 ---------------------------------------------------------------
G9 G1 X20
G9 G1 X-20
G9 G1 Y-9.0

G9 G1 X20
G9 G1 X-20
G9 G1 Y-8.8

G9 G1 X20
G9 G1 X-20
G9 G1 Y-8.6

G9 G1 X20
G9 G1 X-20

---

76
G9 G1 Y-8.4

; round #3
G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 Y-8.2

G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-8.0

G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 Y-7.8

G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-7.6

; round #4
G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-7.4

G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-7.2

G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-7.0

G9 G1 X20
G9 G1 X-20
G9 G1 X20
G9 G1 X-20
G9 G1 Y-6.8

; pausing there for 3 seconds, stop the program here
G4 F3
Curved waveguide study (partial)

; setting to mm/sec
G76

; setting to absolute movements not relative
G90

; setting the feed rate to 10mm/sec
F10

; starting point in x and y axis
G1 X0 Y-20

; set max y value
; G35 Y0
; define area from which stage may not exit
; G36 Y P2

; assigning axis I, J, K to X, Y, Z
G16 XYZ

; now selecting plane 1 (ie. X-Y, I-J plane)
G17 ; G18 and G19 select the other planes

; pausing there for 5 seconds
G4 F5

; straight line to beginning of circle #1
G1 X17
G1 Y-15

; now drawing a quarter circle centered at x = 5mm, y = -20mm, with radius 12mm
G3 X5 Y-3 I-12 J0 ; so this is a circle that ends at [5, -3] (and happens
 ; to start at [17, -15] for which the offset to the center
 ; of the circle from the starting point in the X dir is
 ; I = -12 and in the Y dir is J = 0. so this draws 90deg
 ; of the circle.

; straight line back to the starting point
G1 X0
G1 Y-20

; straight line to beginning of circle #2
G1 X15
G1 Y-15

; now drawing a quarter circle with radius 10mm
G3 X5 Y-5 I-10 J0
; straight line back to the starting point
G1 X0
G1 Y-20

; straight line to beginning of circle #3
G1 X13
G1 Y-15

; now drawing a quarter circle with radius 8mm
G3 X5 Y-7 I-8 J0

; straight line back to the starting point
G1 X0
G1 Y-20

; straight line to beginning of circle #4
G1 X11
G1 Y-15

; now drawing a quarter circle with radius 6mm
G3 X5 Y-9 I-6 J0

; straight line back to the starting point
G1 X0
G1 Y-20

; straight line to beginning of circle #5
G1 X9
G1 Y-15

; now drawing a quarter circle with radius 4mm
G3 X5 Y-11 I-4 J0

; straight line back to the starting point
G1 X0
G1 Y-20

; straight line to beginning of circle #6
G1 X7
G1 Y-15

; now drawing a quarter circle with radius 2mm
G3 X5 Y-13 I-2 J0

; straight line back to the starting point
G1 X0
G1 Y-20

; pausing there for 5 seconds
G4 F5
; stop the program here, remove the sample and home the stages later

; final homing X and Y axis
; G1 X0 Y0

; disabling the safe zone
; G37 Y

---

1:2 Splitter

; setting to mm/sec
G76

; setting to absolute movements not relative
G90

; setting the feed rate to 10mm/sec
F10

; starting point in x and y axis
G9 G1 X-20 Y1

; pausing there for 4 seconds
G4 F4

; enable blending of curves
G108

G1 X-10 Y0
G1 X-5 Y0
G1 X5 Y0.02
G9 G1 X10 Y0.02

; pausing there for 4 seconds
G4 F4

; starting point in x and y axis
G9 G1 X-20 Y1

; pausing there for 4 seconds
G4 F4

G1 X-10 Y0
G1 X-5 Y0
G1 X5 Y-0.02
G9 G1 X10 Y-0.02
; pausing there for 4 seconds
G4 F4

; back to beginning
G9 G1 X-20 Y1

1:3 Splitter

; center z = 0.017

; setting to mm/sec
G76

; setting to absolute movements not relative
G90

; setting the feed rate to 10mm/sec
F10

; starting point in x and y axis
G9 G1 X10 Y0.02 Z0

; pausing there for 4 seconds
G4 F4

; enable blending of curves
G108

G1 X5 Y0.02 Z0

G1 X-5 Y0 Z0.017
G9 G1 X-10 Y0 Z0.017

; pausing there for 4 seconds
G4 F4

; starting point in x and y axis
G9 G1 X10 Y-0.02 Z0

; pausing there for 4 seconds
G4 F4

G1 X5 Y-0.02 Z0

G1 X-5 Y0 Z0.017
G9 G1 X-10 Y0 Z0.017

; pausing there for 4 seconds
G4 F4
Appendix

G1 X-5 Y0 Z0.017
G1 X5 Y0 Z0.034
G9 G1 X10 Y0 Z0.034

; pausing there for 4 seconds
G4 F4

1:4 Splitter

; center z = 0.02
; setting to mm/sec
G76
; setting to absolute movements not relative
G90
; setting the feed rate to 10mm/sec
F10
; starting point in x and y axis
G9 G1 X-10 Y0 Z0.02

; pausing there for 4 seconds
G4 F4

; enable blending of curves
G108
G1 X-5 Y0 Z0.02
G1 X5 Y0.02 Z0.04
G9 G1 X10 Y0.02 Z0.04

; pausing there for 4 seconds
G4 F4
G9 G1 X-10 Y0 Z0.02

; pausing there for 4 seconds
G4 F4
G1 X-5 Y0 Z0.02
G1 X5 Y-0.02 Z0.04
G9 G1 X10 Y-0.02 Z0.04

; pausing there for 4 seconds
G4 F4
G9 G1 X-10 Y0 Z0.02
G9 G1 X10 Y0.02 Z0

; pausing there for 4 seconds
G4 F4
G1 X5 Y0.02 Z0
G1 X-5 Y0 Z0.02
G9 G1 X-10 Y0 Z0.02

; pausing there for 4 seconds
G4 F4

; starting point in x and y axis
G9 G1 X10 Y-0.02 Z0

; pausing there for 4 seconds
G4 F4
G1 X5 Y-0.02 Z0
G1 X-5 Y0 Z0.02
G9 G1 X-10 Y0 Z0.02

; pausing there for 4 seconds
G4 F4
Bibliography


Bibliography


Bibliography


