- Invited paper -

Optical waveguide fabrication for integrated photonic devices

Rafael R. Gattass, Loren R. Cerami and Eric Mazur
Division of Engineering and Applied Sciences, Harvard University
9 Oxford Street, Cambridge MA 02138, USA

ABSTRACT

The dynamic nature of future optical networks requires high levels of integration, fast response times, and adaptability of the optical components. Laser micromachining circumvents the limitations of planar integration, allowing both three-dimensional integration and dense packaging of optical devices without alignment requirements. Femtosecond micromachining enables the analog of circuit printing by wiring light between photonic devices in addition to printing the actual photonic device into single or multiple substrates. Femtosecond laser oscillator-only micromachining has several advantages over amplified femtosecond laser micromachining: easy control over the size of the structures without changing focusing, polarization-independent structures, lower initial investment cost and higher-speed manufacturing. In this paper we review recent results obtained in the field of femtosecond micromachining.

Keywords: Femtosecond, micromachining, nonlinear absorption.

1. INTRODUCTION

The interaction between intense laser pulses and transparent materials is a topic of great interest in research today, as it holds value in both basic and applied scientific research. Intense femtosecond pulses enable highly localized material modification in virtually any transparent material providing an excellent tool for fabricating optical microstructures [1]. The confinement of the nonlinear interaction between the femtosecond laser pulse and the medium to the focal volume allows precise micromachining in three dimensions inside the bulk of the sample. Recent advances in femtosecond laser micromachining have made it possible to "wire light" from one point to another inside a transparent material, opening the door to manufacturing entirely monolithic, integrated optical circuits [2-6].

Alternative three-dimensional optical circuitry manufacturing technologies include Si-based chemical vapor deposition (CVD) [7-9], polymers [10-12], and sol-gels based on CVD [13, 14]. In this paper, we review the current state of the field of femtosecond micromachining with an emphasis on oscillator-only femtosecond micromachining as a tool for wiring light. Oscillator-only micromachining of dielectric materials should not be confused with oscillator based two-photon polymerization, a subject not discussed in this review. Femtosecond micromachining is only a very small part of the vast field of high power laser interactions with materials, of which many excellent reviews are available [15-20].

2. ABSORPTION MECHANISM

Femtosecond laser micromachining is based on the concept of laser-induced optical breakdown, a process by which optical energy is transferred to the material, causing ionization of a large number of electrons. The ionized electrons, in turn, can cause permanent material modification by transferring energy to the lattice. In transparent materials, the energy of a single photon in the visible or infrared cannot be absorbed (which is why the material is transparent), so the absorption process is inherently nonlinear. For such multiphoton absorption to occur, the electric field strength in the laser pulse must be on the order of the electric field that binds the valence electrons in atoms. To achieve the photon density required to generate such high electric field strengths it is necessary to focus the light tightly. The tight focusing and the nonlinear nature of the absorption make it possible to confine the absorption to the focal volume inside the bulk of the material without causing any absorption at the surface. The result is a very localized deposition of energy in the bulk of the sample. As the deposited energy is converted into thermal energy, the material can undergo a phase or structural modification, leaving behind a localized permanent change in index of refraction.

The field of nonlinear absorption of sub-picosecond laser irradiation started a decade ago with surface damage energy threshold experiments [21, 22]. The goal of these measurements was to determine both the pulse duration dependence of the surface damage threshold and the dominant ionization mechanism. Bulk damage experiments using femtosecond lasers were first carried out in 1996 [23]. Studies of the effect of parameters such as pulse duration, pulse center wavelength, and material band gap on nonlinear absorption in transparent materials led to great advances in the this field over the past decade [21, 22, 24-34].

The nonlinear absorption is caused by a combination of photoionization (multiphoton absorption and/or tunneling ionization) and avalanche ionization. A theory for photoionization, unifying tunneling and multiphoton absorption, was introduced by Keldysh in 1965 [35]. Measurements of avalanche ionization rates led to improvements of the Keldysh theory [26, 29, 31, 36], which still remains the base to understanding and quantifying tunneling and multiphoton ionization of carriers by sub-picosecond pulses [24-26]. Quantitative modeling of the interaction is limited by the lack of values for the scattering cross-sections for various ionization mechanisms [34]. Experimentally, fluence damage thresholds are used to determine the ionization mechanisms contributions. Several techniques for determining this threshold have been used [21, 25, 26, 28, 29, 31, 33], but in 2001 the use of a dark-field scattering technique and proper assessment of self-focusing contributions increased the accuracy of the experimental damage threshold values [34].

The damage threshold values indicate that the contributions from the various ionizations mechanisms in large band gap dielectrics depend on the laser parameters. For 800-nm laser pulse irradiation, multiphoton absorption is dominant for sub-10 fs pulses [29], whereas avalanche ionization is the primary mechanism for pulses of 30-200 fs [34]. With 400-nm irradiation, multiphoton absorption can explain the induced damage [34]. As a general rule, the observed intensity threshold for non-linear absorption increases slightly with the band gap of the material, but much less than one would expect on the basis of multiphoton excitation alone for 800-nm, 100-fs pulses.

Research efforts originally focused on understanding nonlinear absorption mechanisms in laser ablation [22, 27, 29, 37-40], but the advent of femtosecond laser machined optical waveguides in 1996 [2] shifted the research interest toward controlling the damage morphology for device applications [3, 41-48]. The processes that occur after the electrons are excited are still poorly understood. These processes are being studied by determining the dependence of the damage morphology on laser pulse energy and focusing conditions using electron and optical microscopy [23, 34, 49], measurements of stress/strain contributions to the resulting index of refraction by transmission electron microscopy and Normansky microscopy [50-52], and by measurement of Raman-identified densification and annealing effects to morphology and index of refraction [53, 54].

Initial understanding of the structural change generated by damage came from single-pulse experiments. The effect of a single, tightly-focused energetic pulse with a fluence well above the damage threshold was observed in *post mortem* studies of fused silica [23, 34, 49]. The dynamics — from the laser excitation of carriers on the femtosecond scale to material motion on the microsecond scale — was studied using a pump-probe imaging setup in water [55]. The time-resolved images show a rapid plasma expansion and subsequent induced shock waves. The rapid plasma expansion observed in liquids explains the voids generated at high pulse energies in solids. For laser fluence near the damage threshold fluence, less energy is transferred to the plasma causing a less drastic structural change, which manifests itself optically in a small index of refraction change, on the order of 10^{-3}.

Femtosecond laser waveguide fabrication involves hundreds of laser pulses. Depending on the time interval between the laser pulses we can distinguish between two different regimes. For large pulse-to-pulse intervals (> 1 μs), the index modification is mainly due to densification, stress and color-centers. Transmission electron microscopy and stress/strain measurements indicate a dependence of the index on the laser polarization [52] while Raman measurements point to local density changes [56]. The densification in fused silica can be attributed to a freezing of the higher density structure at a high glass fictive temperature by rapid annealing [57]. This model is consistent with the difficulty in reproducing densifications in other glasses [6] as most have lower densities at high temperatures [58]. Although densification is an appropriate explanation for the index change in fused silica and Ge-doped silica [59] it is not necessarily valid for all systems. The contribution of color centers can often be ruled out because the density of color centers required for an index change of 10^{-4} needs to be on the order of 10^{15} per cm^3 in fused silica [60]. Moreover, annealing of the sample does not alter the refractive index change [2, 43, 61]. If we take into account not only the magnitude of the index but its spatial distribution [2, 48, 62, 63] the most likely contributors to the index change are a combination of densification and strain.

At short pulse-to-pulse intervals (< 1 μs), accumulation of the energy of multiple pulses causes structural changes due to heat diffusion and rapid annealing [64]. Recent work at very low pulse energies suggests that below threshold incubation effects due to color center formation occur [48, 60]. Modeling the thermal diffusion of the heat deposited by multiple pulses as a function of the number of irradiated pulses agrees well with experimental data at low pulse numbers (below 10^4). At large pulse numbers ($> 10^4$), however, discrepancies occur because the temperature dependence of the thermal diffusion coefficient is not known.

3. HIGH REPETITION RATE MICROMACHINING

Micromachining with femtosecond pulses of just nanojoules eliminating the need for laser amplification and can be achieved with just a laser oscillator [3]. The key to lowering the energy threshold is very tight focusing: at numerical apertures above 1.0, the threshold energy drops below the pulse energy delivered by a femtosecond laser oscillator. Oscillator-only micromachining is fundamentally different from micromachining with amplified laser systems. Because the average output power is limited by the pump source, there is a trade-off between the pulse energy and pulse repetition rate of femtosecond lasers. The time interval between the pulses emitted by a femtosecond laser oscillator is on the order of tens of nanoseconds, which is significantly shorter than the 1-μs heat diffusion time out of the focal volume. Consequently, there is not enough time between successive pulses for the energy deposited by the laser pulse to diffuse out of the focal volume. Over time, the energy from successive pulses accumulates in and around the focal volume, producing damage (see Figure 1). The train of oscillator pulses constitutes a "point source of heat" at the focal volume within the bulk of the material. The longer the material is exposed to the train of pulses from an oscillator, the higher the temperature at the focus and the larger the region that is heated. If the temperature exceeds the material's melting point, structural changes can occur. Melting and resolidification of material occurs up to a radius of 50 μm [3]. The pulses from an amplified femtosecond laser system, on the other hand, typically are separated by milliseconds, far exceeding the time required for heat to diffuse out of the focal volume. The focal volume thus equilibrates to the bulk temperature before the next pulse arrives. Consequently, the structural change caused by an amplified laser is confined to the focal volume, regardless of the number of pulses that strike the sample.

To determine the transition between cumulative heat deposition and single-pulse damage, we investigated the dependence of the morphology of the laser-induced structural change on the number of pulses and on the laser repetition rate. The repetition rate is varied using an acousto-optic modulator located outside the laser cavity. An electronic signal that is synchronized with the laser repetition rate is used to select a set of pulses from the laser pulse train and deliver it to the sample (Figure 2). The pulse rate can be gated, allowing fractions of the original repetition rate to be achieved (Figure 2a). The external modulator also allows packets of pulses to be delivered at various repetition rates (Figure 2b and 2c). Figure 3 shows transmission optical microscopy images of Corning 0215 glass irradiated with 5.5-nJ, 55-fs pulses focused by a 1.4 numerical aperture objective in packets containing 10 pulses. The repetition rate varies in the horizontal direction and the total number of pulses deposited in the sample in the vertical direction. The energy of the laser pulses very close to the threshold energy for damage (about 5 nJ) and so it is reasonable to assume that each individual pulse deposits very little energy. Accumulation of thermal energy thus only occurs when the pulse-to-pulse time is close to the thermal diffusion time, allowing precise determination of the thermal diffusion time. We are currently studying the transition between the high and low repetition rate micromachining regimes for various materials.

4. APPLICATIONS

One of the most exciting applications of femtosecond micromachining of transparent materials is the fabrication of three-dimensional waveguide structures — critical components for future integrated optical "chips." Both femtosecond oscillators and amplified systems have been used to fabricate a number of simple devices, from beam splitters to amplifiers and resonators (Table 1). The change in index of refraction is roughly the same for both low (amplified) and high (unamplified) repetition-rate waveguide writing, although the gamut of materials used for low repetition rate micromachining (below 1 MHz, where pulse energy is not a limitation) is much larger.

At low repetition rates, waveguide writing can be done in several geometries (Figure 4). A simple, but limited way to machine waveguides is to let non-linear effects confine the femtosecond pulses to a self-channeling filament. Typically the self-channeling is achieved with a lens of long focal length and the micromachining occurs throughout the filament. The focusing and input power control the waveguide dimensions. Because the resulting waveguide is necessarily straight, this geometry does not allow the micromachining of devices that include curves or bends. Another widely used geometry is that of longitudinal irradiation: a large working distance objective with a fairly low numerical aperture is used to focus the beam inside the sample, which is translated parallel to the beam during irradiation. Because the waveguide is manufactured parallel to the irradiation direction, the diameter is defined by the transverse beam profile, making it possible to achieve fairly large core diameters. This technique also allows fabrication of curves and bends, but the working distance of the objective limits the length of the waveguide. Transverse micromachining puts no limit on the length of the waveguide, but the cross section of the waveguide typically is elliptical due to the geometry of the focal volume. To obtain a more spherical focal volume and minimize the ellipticity, the beam can be shaped using an astigmatic lens.

In the case of high-repetition rate, oscillator-only micromachining, the geometry is restricted by the maximum pulse energy available. Usually a high numerical aperture objective (NA $\geq$ 1) must be used, which necessitates a transverse writing geometry. The diameter of the waveguide is controlled by the translation speed of the sample: the slower the translation speed, the more pulses strike the same spot. When more pulses strike the same spot, the radius to which the material is heated above the melting point increases along with the diameter of the final waveguide structure. Because this diameter is determined by heat diffusion, the cross section of waveguides fabricated this way is very nearly circular. The very high repetition rate of oscillators permits the fabrication of devices at writing speeds that are typically 100–1000 times higher than those obtained with amplified laser systems.

The writing of internal waveguides makes it possible to wire "optical breadboards" and constitutes a major step towards the realization of optical integrated circuits. The devices listed in Table 1 comprise a basic tool chest of passive and active components for integrated optical circuits. Major advantages of optical signal processing over electronic integration are the ability to connect in three-dimensions and the lack of thermal energy dissipation. However, femtosecond laser micromachining is a sequential process — each circuit needs to be wired separately. Oscillator-only micromachining relieves some of this limitation by making it possible to write at very high speeds. In addition, the past few years have seen the rapid development of smaller, simpler, cheaper and more powerful femtosecond laser oscillators. These developments greatly benefit waveguide writing with femtosecond lasers by providing greater control of the diameter of waveguides, increasing the speed at which devices can be made, and greatly broadening the range of materials that can be machined.

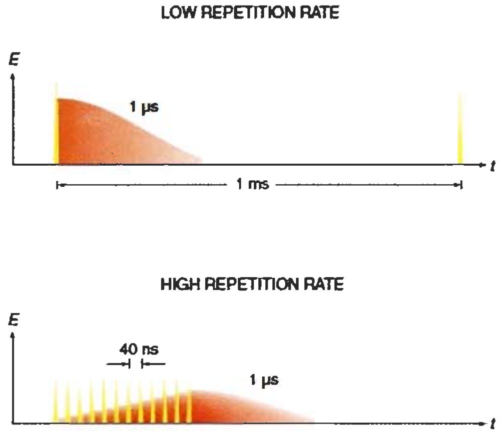

Figure 1 At low repetition rate, the energy deposited by each laser pulse diffuses out of the focal volume before the next pulse arrives. At high repetition rate, however, energy accumulates in the focal volume, making it possible to achieve very high temperatures around the focal volume with pulse energies of just a few nanojoules. Yellow indicates the laser pulses; red the deposited energy.

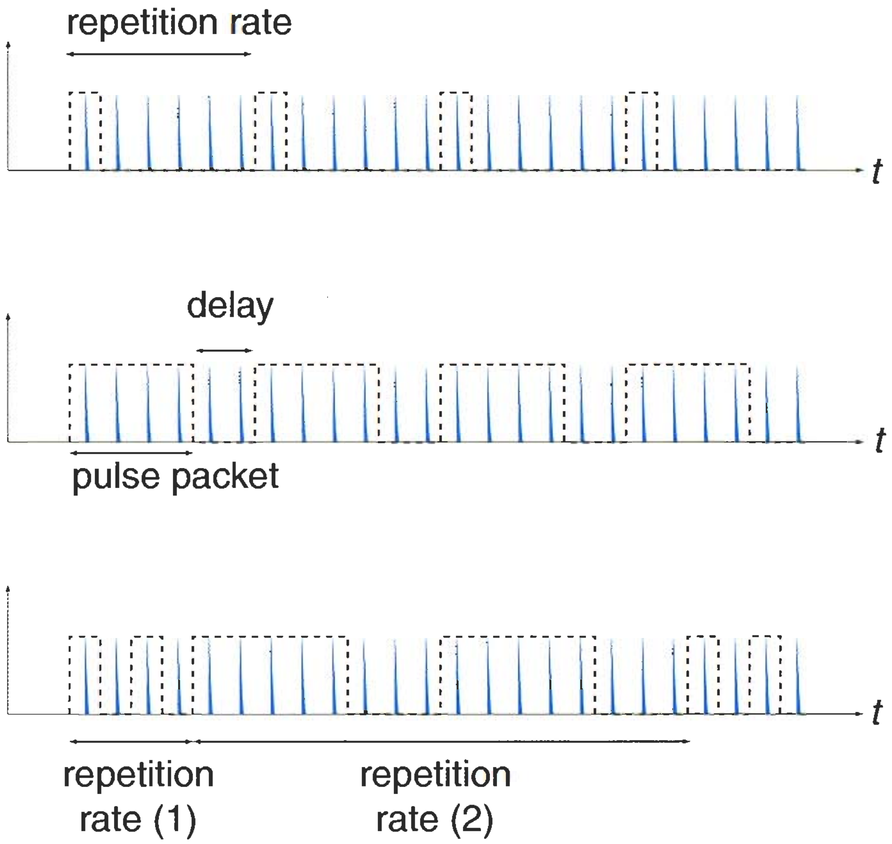

Figure 2 The laser repetition rate can be changed outside the laser cavity using an acousto-optic modulator gated by an electronic signal. The dashed lines indicate the electronic gate pulse. Top: The repetition rate is reduced to 1/6 of the original repetition rate. Middle: Packets of pulses are transmitted at the reduced rate of 1/6 the original repetition rate. Bottom: Alternating repetition rate and the number of pulses within each packet.

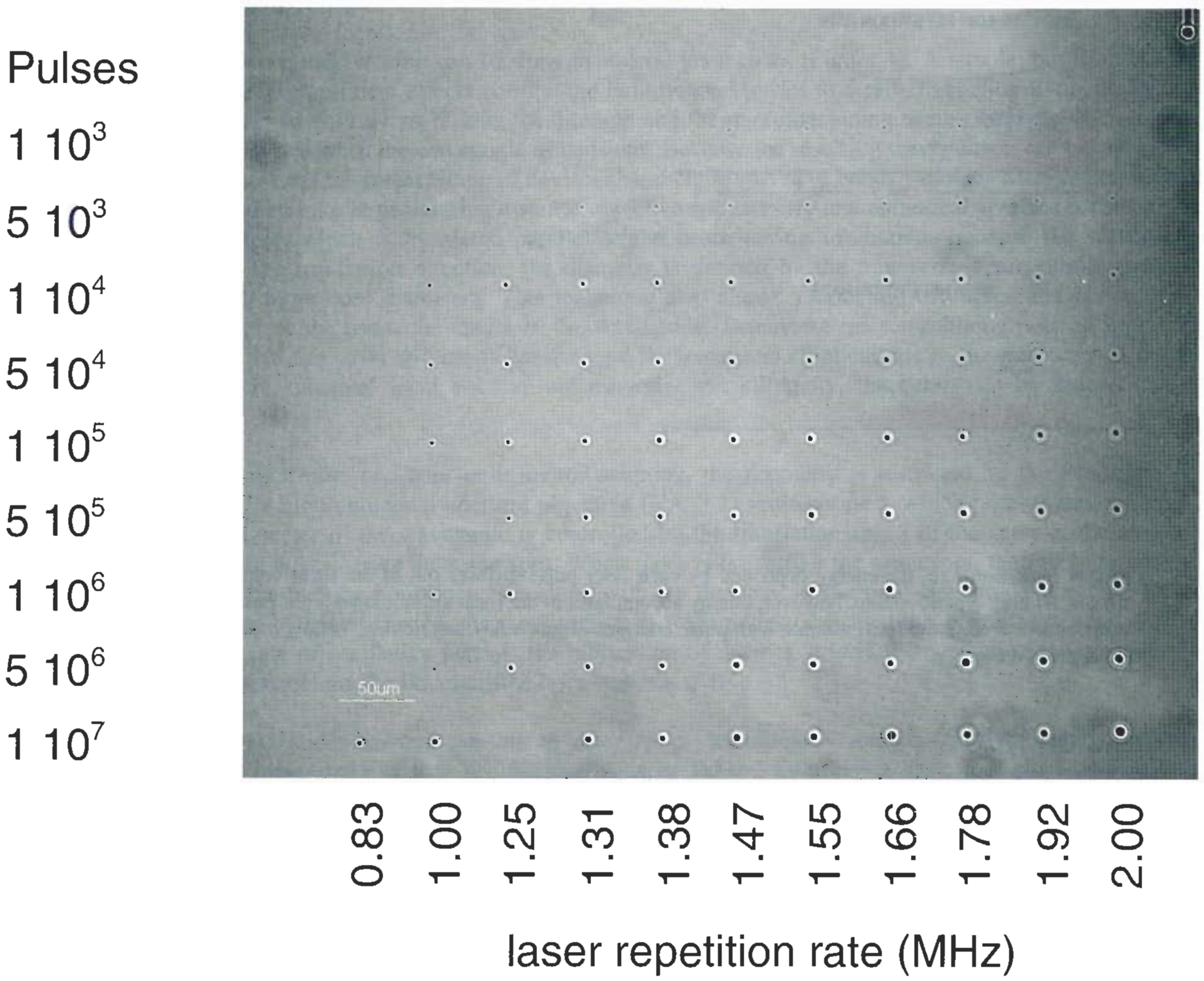

Figure 3 Transmission optical microscope image of Corning 0215 irradiated by pulse packets of 10 pulses at a various laser repetition rates. The vertical scale shows the number of packets delivered.

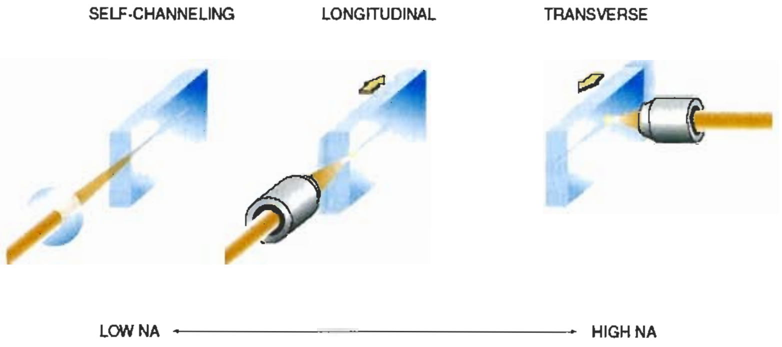

Figure 4 Geometries used for micromachining waveguides in the bulk of transparent samples. The self-channeling and longitudinal geometries are usually used with amplified laser systems; oscillator-only micromachining is done transversely.

Table 1 Optical device components manufactured by femtosecond laser micromachining of transparent materials together with the conditions for fabrication and resulting change in index of refraction. The shaded part of the table shows devices fabricated with just a laser oscillator.

Device	Repetition rate	Pulse energy	NA	Geometry	Writing speed (mm/s)	Index change $(\times 10^{-3})$
Amplifier [41]	0.25 kHz	4 µJ	0.1	longitudinal	0.025	not reported
Mach-Zehnder [42]	0.25 kHz	1–10 µJ	0.55	longitudinal and transverse	0.025–0.200	4
Y-coupler [43]	1 kHz	1 µJ	0.16	self channeling	0.020	3–5
Amplifier [44]	1 kHz	1 µJ	0.3–0.6	beam shaped transverse	0.020	2
Waveguide [46]	1 kHz	20 µJ	0.007	self channeling	not applicable	5
Waveguide [2]	200 kHz	0.2–4 µJ	0.10–0.25	transverse and longitudinal	0.010	10
Mach-Zehnder [45]	4 MHz	20 nJ	0.6	transverse	10	1–5
Waveguide [3]	25 MHz	5 nJ	1.4	transverse	20	0.3
Waveguide [48]	80 MHz	7–9 nJ	0.26	longitudinal	0.001–0.100	5

References:

[1] E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, P. Callan, and E. Mazur, "3-D Optical data storage and engraving in transparent materials," in *Ultrafast Phenomena X*, Ed. P.F. Barbara, J.G. Fujimoto, W.H. Knox, and W. Zinth Berlin: Springer Verlag, 1996, pp. 157-158.

[2] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," Optics Letters, vol. 21, pp. 1729-1731, 1996.

[3] C. B. Schaffer, A. Brodeur, J. F. Garcia, and E. Mazur, "Micromachining bulk glass by use of femtosecond laser pulses with nanojoule energy," *Optics Letters*, vol. 26, pp. 93-95, 2001.

[4] K. Minoshima, A. M. Kowalevicz, E. P. Ippen, and J. G. Fujimoto, "Fabrication of coupled mode photonic devices in glass by nonlinear femtosecond laser materials processing," *Optics Express*, vol. 10, pp. 645-652, 2002.

[5] B. Yu, B. Chen, X. Y. Yang, J. R. Qiu, X. W. Jiang, C. S. Zhu, and K. Hirao, "Study of crystal formation in borate, niobate, and titanate glasses irradiated by femtosecond laser pulses," *Journal of The Optical Society of America B-Optical Physics*, vol. 21, pp. 83-87, 2004.

[6] S. Nolte, M. Will, J. Burghoff, and A. Tuennermann, "Femtosecond waveguide writing: a new avenue to three-dimensional integrated optics," *Applied Physics A-Materials Science & Processing*, vol. 77, pp. 109-111, 2003.

[7] T. Miya, "Silica-based planar lightwave circuits: Passive and thermally active devices," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, pp. 38-45, 2000.

[8] A. G. Rickman, G. T. Reed, and F. Namavar, "Silicon-On-Insulator Optical Rib Wave-Guide Loss And Mode Characteristics," *Journal of Lightwave Technology*, vol. 12, pp. 1771-1776, 1994.

[9] P. D. Trinh, S. Yegnanarayanan, and B. Jalali, "Integrated Optical Directional-Couplers In Silicon-On-Insulator," *Electronics Letters*, vol. 31, pp. 2097-2098, 1995.

[10] L. Eldada, "Advances in telecom and datacom optical components," *Optical Engineering*, vol. 40, pp. 1165-1178, 2001.

[11] L. Eldada and L. W. Shacklette, "Advances in polymer integrated optics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, pp. 54-68, 2000.

[12] J. Serbin, A. Egbert, A. Ostendorf, B. N. Chichkov, R. Houbertz, G. Domann, J. Schulz, C. Cronauer, L. Frohlich, and M. Popall, "Femtosecond laser-induced two-photon polymerization of inorganic-organic hybrid materials for applications in photonics," *Optics Letters*, vol. 28, pp. 301-303, 2003.

[13] E. M. Yeatman and E. J. C. Dawnay, "Doped sol-gel films for silica-on-silicon photonic components," *Journal of Sol-Gel Science and Technology*, vol. 8, pp. 1007-1011, 1997.

[14] A. B. Seddon, "Sol-gel derived organic-inorganic hybrid materials for photonic applications," *IEE Proceedings-Circuits Devices and Systems*, vol. 145, pp. 369-372, 1998.

[15] N. Bloembergen, "Laser-Induced Electric Breakdown In Solids," *IEEE Journal of Quantum Electronics*, vol. QE10, pp. 375-386, 1974.

[16] T. Brabec and F. Krausz, "Intense few-cycle laser fields: Frontiers of nonlinear optics," *Reviews of Modern Physics*, vol. 72, pp. 545-591, 2000.

[17] Y. R. Shen, *The Principles of Nonlinear Optics*, Wiley classics library ed. Hoboken, N.J.: Wiley-Interscience, 2003.

[18] N. Bloembergen, *Nonlinear Optics*, 4th ed. Singapore: World Scientific, 1996.

[19] R. W. Boyd, *Nonlinear Optics*, 2nd ed. Amsterdam: Academic Press, 2003.

[20] G. P. Agrawal, *Applications of Nonlinear Fiber Optics*. San Diego: Academic Press, 2001.

[21] D. Du, X. Liu, G. Korn, J. Squier, and G. Mourou, "Laser-Induced Breakdown By Impact Ionization In SiO_2 With Pulse Widths From 7 ns to 150 fs," *Applied Physics Letters*, vol. 64, pp. 3071-3073, 1994.

[22] B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry, "Laser-Induced Damage In Dielectrics With Nanosecond To Subpicosecond Pulses," *Physical Review Letters*, vol. 74, pp. 2248-2251, 1995.

[23] E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, P. Callan, and E. Mazur, "Three-dimensional optical storage inside transparent materials," *Optics Letters*, vol. 21, pp. 2023-2025, 1996.

[24] D. Du, X. Liu, and G. Mourou, "Reduction of multi-photon ionization in dielectrics due to collisions," *Applied Physics B-Lasers and Optics*, vol. 63, pp. 617-621, 1996.

[25] B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, "Optical ablation by high-power short-pulse lasers," *Journal of The Optical Society of America B-Optical Physics*, vol. 13, pp. 459-468, 1996.

[26] B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, "Nanosecond-to-femtosecond laser-induced breakdown in dielectrics," *Physical Review B*, vol. 53, pp. 1749-1761, 1996.

[27] D. vonderLinde and H. Schuler, "Breakdown threshold and plasma formation in femtosecond laser-solid interaction," *Journal of The Optical Society of America B-Optical Physics*, vol. 13, pp. 216-222, 1996.

[28] H. Varel, D. Ashkenasi, A. Rosenfeld, R. Herrmann, F. Noack, and E. E. B. Campbell, "Laser-induced damage in SiO2 and CaF2 with picosecond and femtosecond laser pulses," *Applied Physics A-Materials Science & Processing*, vol. 62, pp. 293-294, 1996.

[29] M. Lenzner, J. Kruger, S. Sartania, Z. Cheng, C. Spielmann, G. Mourou, W. Kautek, and F. Krausz, "Femtosecond optical breakdown in dielectrics," *Physical Review Letters*, vol. 80, pp. 4076-4079, 1998.

[30] M. Lenzner, J. Kruger, W. Kautek, and F. Krausz, "Precision laser ablation of dielectrics in the 10-fs regime," *Applied Physics A-Materials Science & Processing*, vol. 68, pp. 369-371, 1999.

[31] A. C. Tien, S. Backus, H. Kapteyn, M. Murnane, and G. Mourou, "Short-pulse laser damage in transparent materials as a function of pulse duration," *Physical Review Letters*, vol. 82, pp. 3883-3886, 1999.

[32] A. Rosenfeld, M. Lorenz, R. Stoian, and D. Ashkenasi, "Ultrashort-laser-pulse damage threshold of transparent materials and the role of incubation," *Applied Physics A-Materials Science & Processing*, vol. 69, pp. S373-S376, 1999.

[33] M. Li, S. Menon, J. P. Nibarger, and G. N. Gibson, "Ultrafast electron dynamics in femtosecond optical breakdown of dielectrics," *Physical Review Letters*, vol. 82, pp. 2394-2397, 1999.

[34] C. B. Schaffer, A. Brodeur, and E. Mazur, "Laser-induced breakdown and damage in bulk transparent materials induced by tightly-focused femtosecond laser pulses," *Measurement Science and Technology*, vol. 12, pp. 1784-1794, 2001.

[35] L. V. Keldysh, "Ionization In Field Of A Strong Electromagnetic Wave," *Soviet Physics JETP-USSR*, vol. 20, pp. 1307-&, 1965.

[36] K. K. Thornber, "Applications Of Scaling To Problems In High-Field Electronic Transport," *Journal of Applied Physics*, vol. 52, pp. 279-290, 1981.

[37] H. Varel, D. Ashkenasi, A. Rosenfeld, M. Wahmer, and E. E. B. Campbell, "Micromachining of quartz with ultrashort laser pulses," *Applied Physics A-Materials Science & Processing*, vol. 65, pp. 367-373, 1997.

[38] J. Kruger and W. Kautek, "Femtosecond-pulse visible laser processing of transparent materials," *Applied Surface Science*, vol. 96-8, pp. 430-438, 1996.

[39] P. P. Pronko, S. K. Dutta, J. Squier, J. V. Rudd, D. Du, and G. Mourou, "Micromachining Of Submicron Holes Using A Femtosecond Laser At 800-Nm," *Optics Communications*, vol. 114, pp. 106-110, 1995.

[40] X. B. Liu and G. Mourou, "Ultrashort laser pulses tackle precision micromachining," *Laser Focus World*, vol. 33, pp. 101, 1997.

[41] Y. Sikorski, A. A. Said, P. Bado, R. Maynard, C. Florea, and K. A. Winick, "Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses," *Electronics Letters*, vol. 36, pp. 226-227, 2000.

[42] C. Florea and K. A. Winick, "Fabrication and characterization of photonic devices directly written in glass using femtosecond laser pulses," *Journal of Lightwave Technology*, vol. 21, pp. 246-253, 2003.

[43] D. Homoelle, S. Wielandy, A. L. Gaeta, N. F. Borrelli, and C. Smith, "Infrared photosensitivity in silica glasses exposed to femtosecond laser pulses," *Optics Letters*, vol. 24, pp. 1311-1313, 1999.

[44] R. Osellame, S. Taccheo, M. Marangoni, R. Ramponi, P. Laporta, D. Polli, S. De Silvestri, and G. Cerullo, "Femtosecond writing of active optical waveguides with astigmatically shaped beams," *Journal of The Optical Society of America B-Optical Physics*, vol. 20, pp. 1559-1567, 2003.

[45] K. Minoshima, A. M. Kowalevicz, I. Hartl, E. P. Ippen, and J. G. Fujimoto, "Photonic device fabrication in glass by use of nonlinear materials processing with a femtosecond laser oscillator," *Optics Letters*, vol. 26, pp. 1516-1518, 2001.

[46] M. Kamata and M. Obara, "Control of the refractive index change in fused silica glasses induced by a loosely focused femtosecond laser," *Applied Physics A-Materials Science & Processing*, vol. 78, pp. 85-88, 2004.

[47] R. Osellame, N. Chiodo, G. Della Valle, S. Taccheo, R. Ramponi, G. Cerullo, A. Killi, U. Morgner, M. Lederer, and D. Kopf, "Optical waveguide writing with a diode-pumped femtosecond oscillator," *Optics Letters*, vol. 29, pp. 1900-1902, 2004.

[48] A. M. Streltsov and N. F. Borrelli, "Fabrication and analysis of a directional coupler written in glass by nanojoule femtosecond laser pulses," *Optics Letters*, vol. 26, pp. 42-43, 2001.

[49] E. N. Glezer and E. Mazur, "Ultrafast-laser driven micro-explosions in transparent materials," *Applied Physics Letters*, vol. 71, pp. 882-884, 1997.

[50] B. Poumellec, L. Sudrie, M. Franco, B. Prade, and A. Mysyrowicz, "Femtosecond laser irradiation stress induced in pure silica," *Optics Express*, vol. 11, pp. 1070-1079, 2003.

[51] F. Durr, H. G. Limberger, R. P. Salathe, F. Hindle, M. Douay, E. Fertein, and C. Przygodzki, "Tomographic measurement of femtosecond-laser induced stress changes in optical fibers," *Applied Physics Letters*, vol. 84, pp. 4983-4985, 2004.

[52] T. Gorelik, M. Will, S. Nolte, A. Tuennermann, and U. Glatzel, "Transmission electron microscopy studies of femtosecond laser induced modifications in quartz," *Applied Physics A-Materials Science & Processing*, vol. 76, pp. 309-311, 2003.

[53] J. W. Chan, T. R. Huser, S. H. Risbud, and D. M. Krol, "Modification of the fused silica glass network associated with waveguide fabrication using femtosecond laser pulses," *Applied Physics A-Materials Science & Processing*, vol. 76, pp. 367-372, 2003.

[54] J. W. Chan, T. Huser, S. Risbud, and D. M. Krol, "Structural changes in fused silica after exposure to focused femtosecond laser pulses," *Optics Letters*, vol. 26, pp. 1726-1728, 2001.

[55] C. B. Schaffer, N. Nishimura, E. N. Glezer, A. M. T. Kim, and E. Mazur, "Dynamics of femtosecond laser-induced breakdown in water from femtoseconds to microseconds," *Optics Express*, vol. 10, pp. 196-203, 2002.

[56] W. Reichman, J. W. Chan, and D. M. Krol, "Confocal fluorescence and Raman microscopy of femtosecond laser-modified fused silica," *Journal of Physics-Condensed Matter*, vol. 15, pp. S2447-S2456, 2003.

[57] A. E. Geissberger and F. L. Galeener, "Raman studies of vitreous SiO_2 versus fictive temperature," *Physical Review B (Condensed Matter)*, vol. 28, pp. 3266, 1983.

[58] J. E. Shelby, *Introduction to Glass Science and Technology*. Cambridge, England: The Royal Society of Chemistry, 1997.

[59] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, "Photosensitivity In Optical Fiber Waveguides - Application To Reflection Filter Fabrication," *Applied Physics Letters*, vol. 32, pp. 647-649, 1978.

[60] A. M. Streltsov and N. F. Borrelli, "Study of femtosecond-laser-written waveguides in glasses," *Journal of The Optical Society of America B-Optical Physics*, vol. 19, pp. 2496-2504, 2002.

[61] M. Will, S. Nolte, B. N. Chichkov, and A. Tunnermann, "Optical properties of waveguides fabricated in fused silica by femtosecond laser pulses," *Applied Optics*, vol. 41, pp. 4360-4364, 2002.

[62] J. B. Ashcom and E. Mazur, "Femtosecond laser-induced microexplosions in transparent materials," presented at LEOS 2001, 2001.

[63] K. Hirao and K. Miura, "Writing waveguides and gratings in silica and related materials by a femtosecond laser," *Journal of Non-Crystalline Solids*, vol. 239, pp. 91-95, 1998.

[64] C. B. Schaffer, J. F. Garcia, and E. Mazur, "Bulk heating of transparent materials using a high repetition-rate femtosecond laser," *Applied Physics A*, vol. 76, pp. 351-354, 2003.