Low-Loss Waveguides Fabricated by Femtosecond Chirped-Pulse Oscillator

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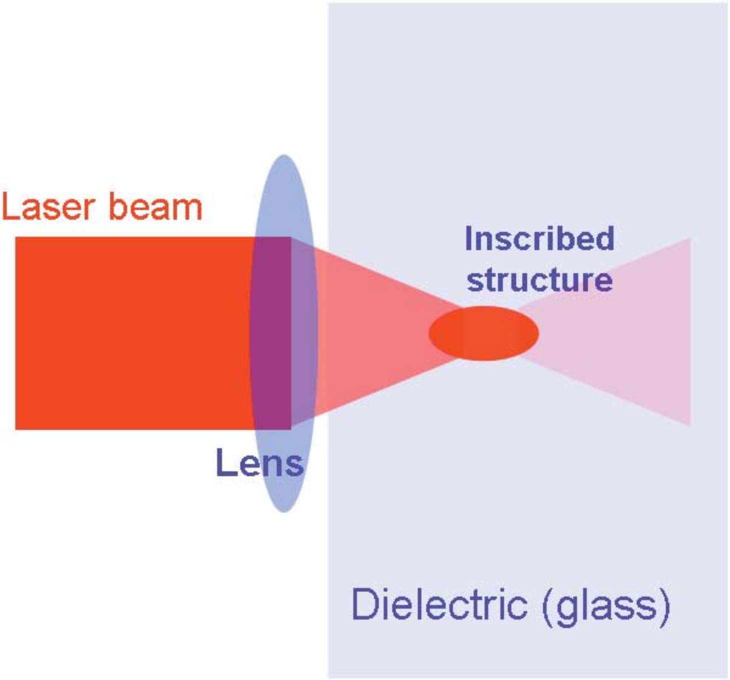
Outline

- Principle of femtosecond microfabrication
- Historic prospective
- Motivation for the present work
- Fs inscription of waveguides
- Waveguide characterisation
- Bending losses
- Conclusions

Principle of femtosecond (fs) microfabrication

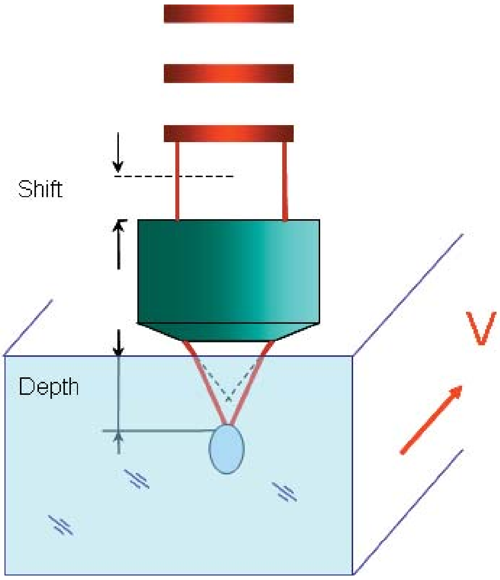
femtosecond microfabrication for dummies



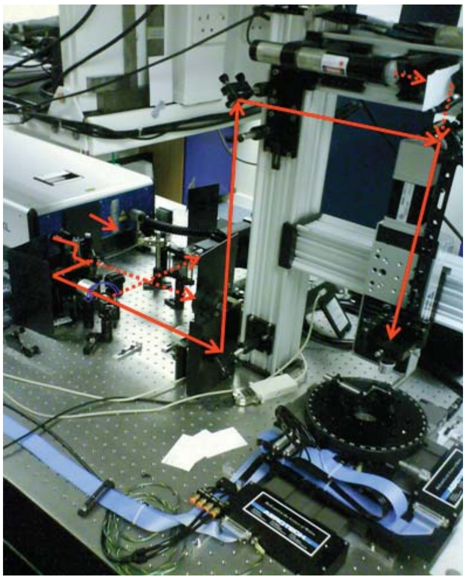
Laser pulse enters left to right

Femtosecond micro-fabrication/machining

Experimental implementation



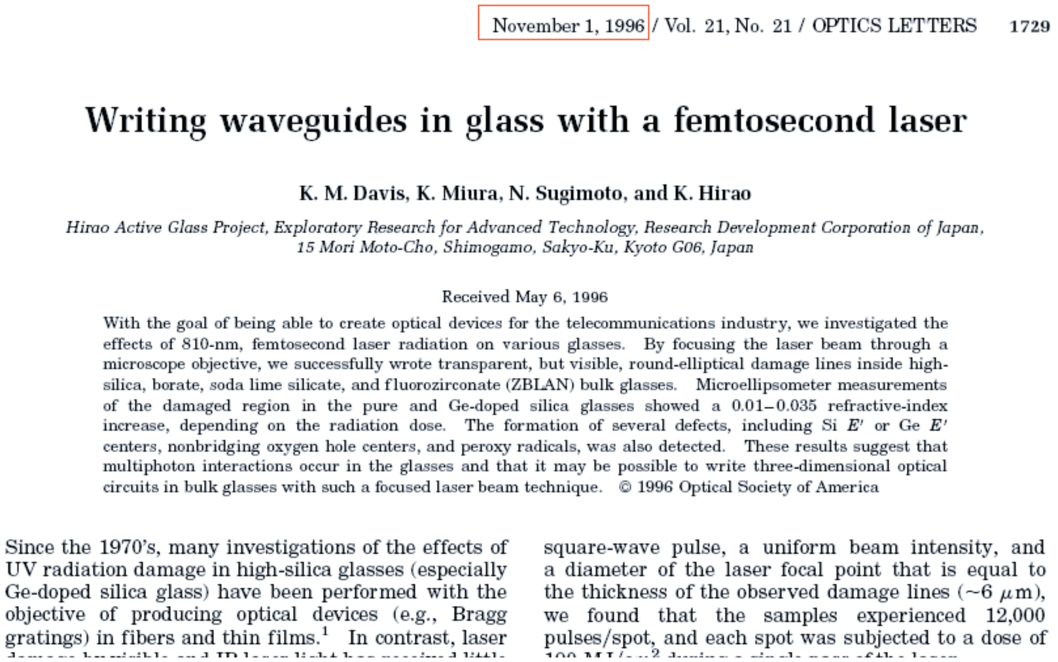
Schematic of fs inscription



Experimental setup

First demonstration of fs microfabrication

[Davis et al Opt. Lett. 1996]



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Writing waveguides in glass with a femtosecond laser

K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao

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Received May 6, 1996

With the goal of being able to create optical devices for the telecommunications industry, we investigated the effects of 810-nm, femtosecond laser radiation on various glasses. By focusing the laser beam through a microscope objective, we successfully wrote transparent, but visible, round-elliptical damage lines inside high-silica, borate, soda lime silicate, and fluorozirconate (ZBLAN) bulk glasses. Microellipsometer measurements of the damaged region in the pure and Ge-doped silica glasses showed a 0.01–0.035 refractive-index increase, depending on the radiation dose. The formation of several defects, including Si E' or Ge E' centers, nonbridging oxygen hole centers, and peroxy radicals, was also detected. These results suggest that multiphoton interactions occur in the glasses and that it may be possible to write three-dimensional optical circuits in bulk glasses with such a focused laser beam technique. © 1996 Optical Society of America

Since the 1970's, many investigations of the effects of UV radiation damage in high-silica glasses (especially Ge-doped silica glass) have been performed with the objective of producing optical devices (e.g., Bragg gratings) in fibers and thin films.[1] In contrast, laser

square-wave pulse, a uniform beam intensity, and a diameter of the laser focal point that is equal to the thickness of the observed damage lines (~6 μm), we found that the samples experienced 12,000 pulses/spot, and each spot was subjected to a dose of

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First demonstration of fs microfabrication

[Davis et al Opt. Lett. 1996]

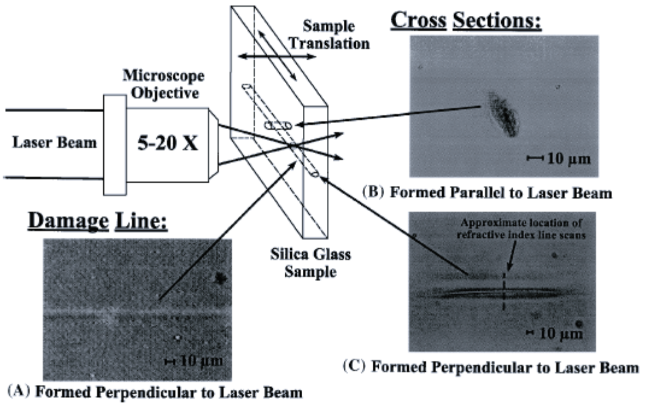


Fig. 1. Laser damage process with images of (A) a laser damage line, (B) the cross section of a line written by translation of the sample parallel to the incident laser beam, and (C) the cross section of a line written by translation of the sample perpendicular to the incident laser beam by a 5× microscope objective. The dashed line in (C) represents the path traversed during the microellipsometer measurements.

Femtosecond micro-fabrication/machining

3D examples

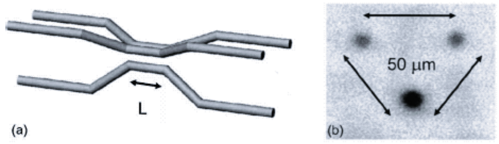


Fig. 1. (a) Schematic of the symmetric three-waveguide directional coupler. Waveguides are initially separated by 50 μm and by 5 μm in interaction region L. (b) Inverse gray-scale CCD image of the waveguide outputs shows a 43:28:29 power-splitting ratio between the guides.

Microfabrication of 3D couplers. Kowalevitz et al, 2005

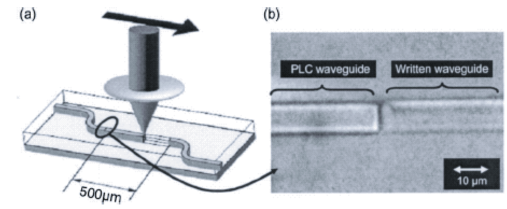


Fig. 5. (a) Schematic diagram of the waveguide connection in this experiment. (b) Image at the junction point of waveguide connection.

Lightwave Circuits. Nasu et al, 2005

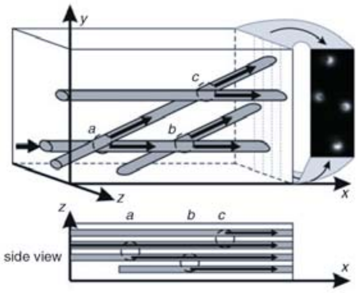


Fig. 3 *Schematic of 1 × 4 splitter (top and side view) with experimenta near-field of output face at 1550 nm*

3D splitter. Osellame et al, 2005

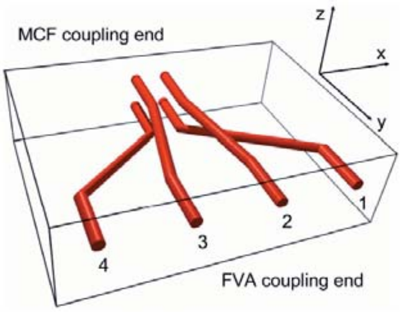


Fig. 1. Graphical representation of the fabricated fan-out device.

Fan out coupler. Thomson et al, 2007

Motivation for the present work

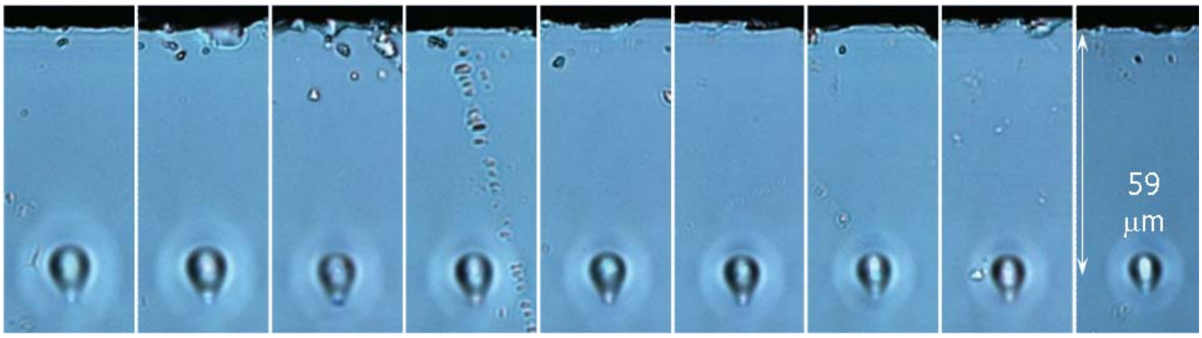
- Find key parameters to achieve well performing curved waveguides in bulk materials
- Produce reliable optimised 2D/2.5D/3D structures ready for applications in integrated optics
- Demonstrate Bragg gratings embedded into waveguides in a single process of wavegiuide inscription.

Choice of a chisel

Parameter	**1 kHz, 800 mJ** **110 fs**	**11 MHz, 100 nJ** **45-55 fs**	**Enh.**
Efficiency (Utilization) of Laser Energy	80-800 nJ (10^{-4})	20–60 nJ (0.2–0.6)	$> 10^3$
Index Contrast, Δn	$> 10^{-3}$	$> 10^{-2}$	10
Translation speed, mm/s	0.01–0.1	10–100	$> 10^3$
WG diameter,mm	< 2	< 20	10

Waveguide inscription

Shown: microphotographs of the waveguide cross-sections for translation speeds 20 to 60 mm/s increasing left to right



All waveguides shown above were inscribed with pulse energy of 30.7 nJ. Focal point was shifted inwards by about 45 μm (actual depth is about 59 μm).

Waveguide inscription

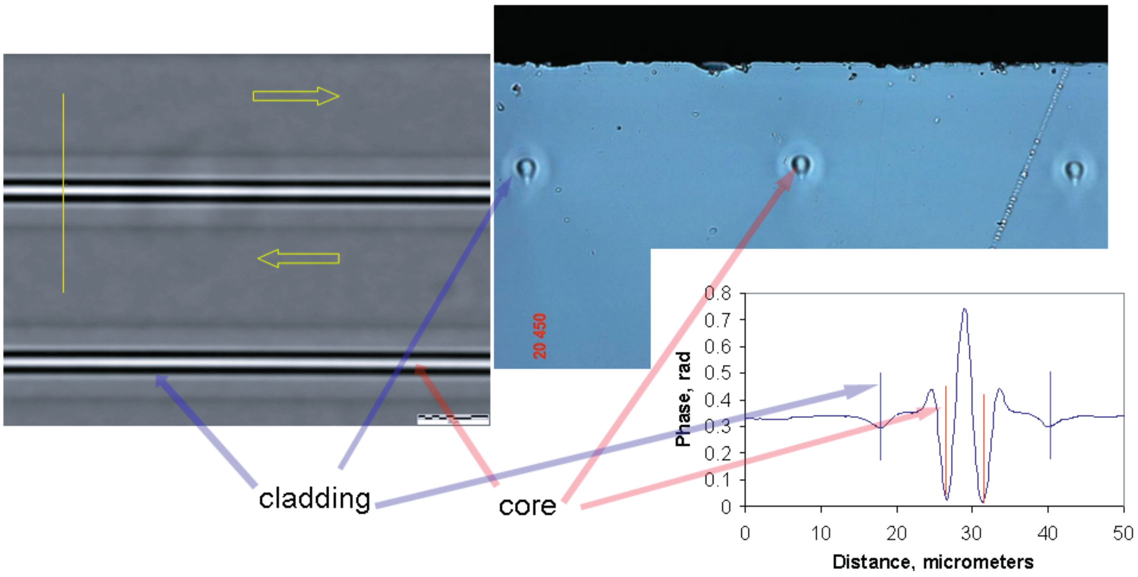
Optimisation parameter space

Optimisation Target: lowest possible total losses of waveguide

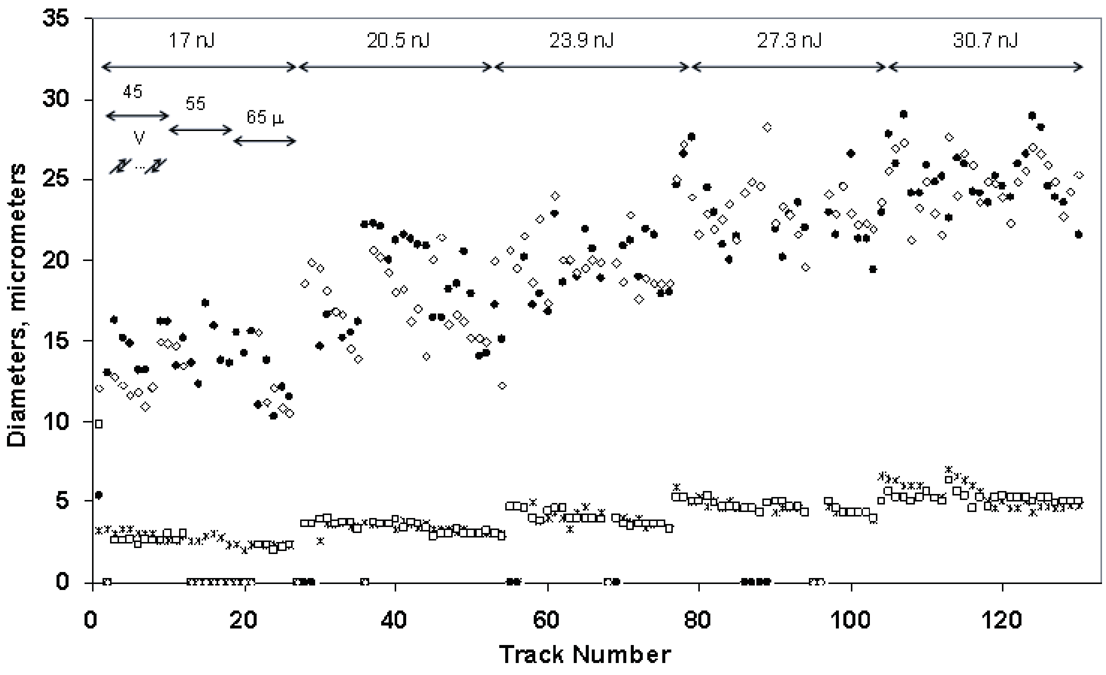
Pulse Energy, nJ	x5	17, 19.2, . . . , 31
Translation speed: mm/s	x9	20, 25, . . . , 55, 60
Inscription depth, mm	x3	68 , 83 and 100
Polarizations:	x2(3)	X – ⊥ and Y – ∥ to scan direction)
Translation direction	x2	Forward and Backward

Total: 540 tracks

Morphology of smooth well performing waveguides

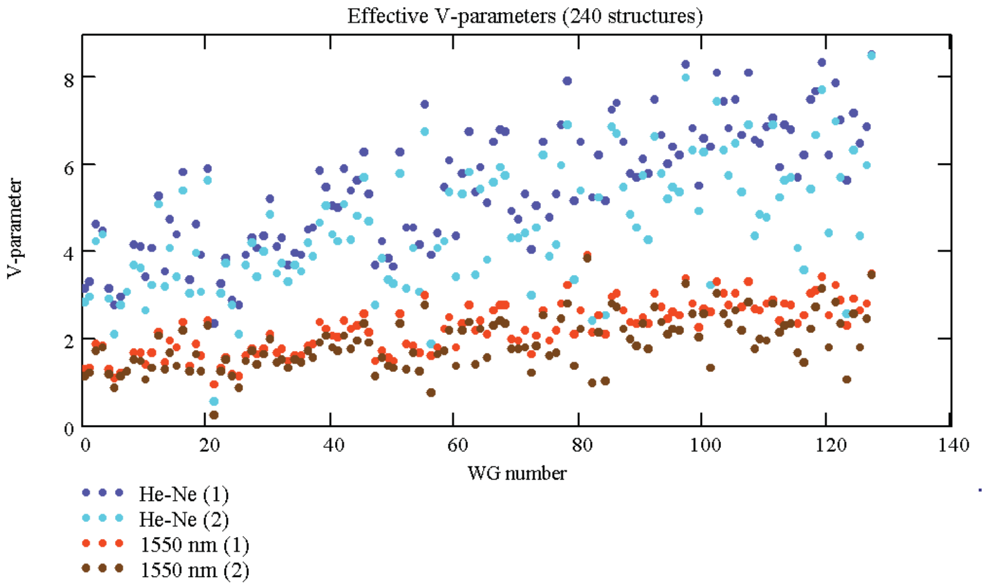


Waveguide diameters



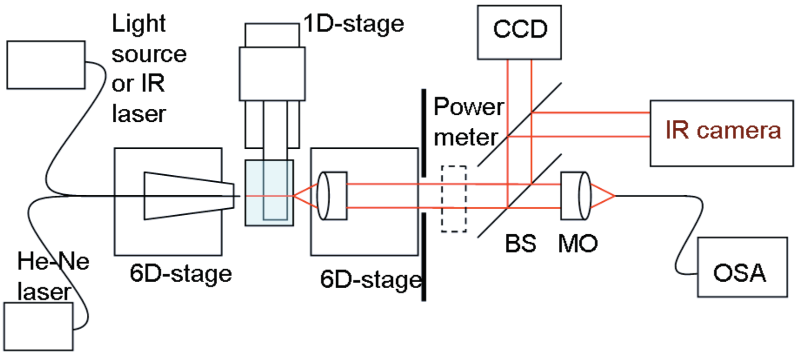
Core and cladding diameters for X (◇ – cladding, □ – core) and Y-polarizations (●– cladding, ∗– core).

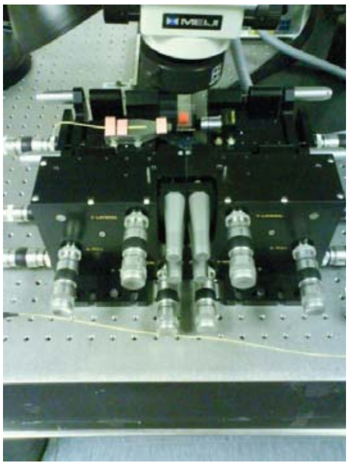
V-parameter for gradient index waveguides

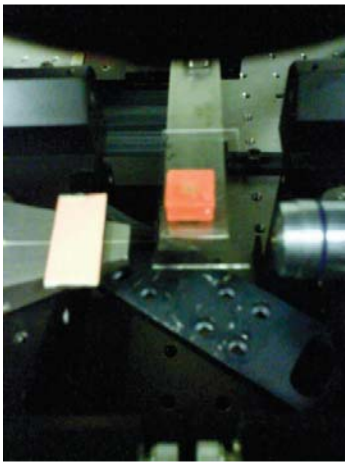


$$V = \frac{2\pi}{\lambda}\sqrt{\int_{0}^{\infty} \left(n^2(r) - n_b^2\right)\, 2r\, dr}$$

A rig for waveguide characterisation

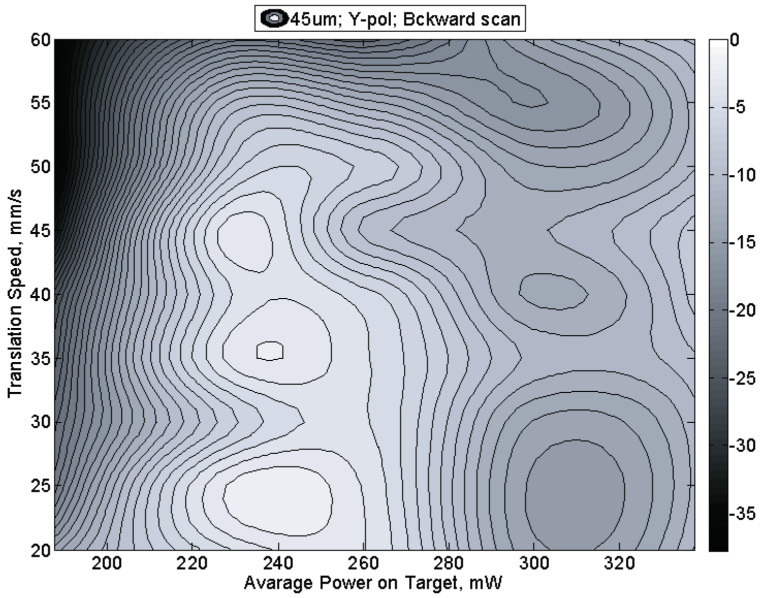






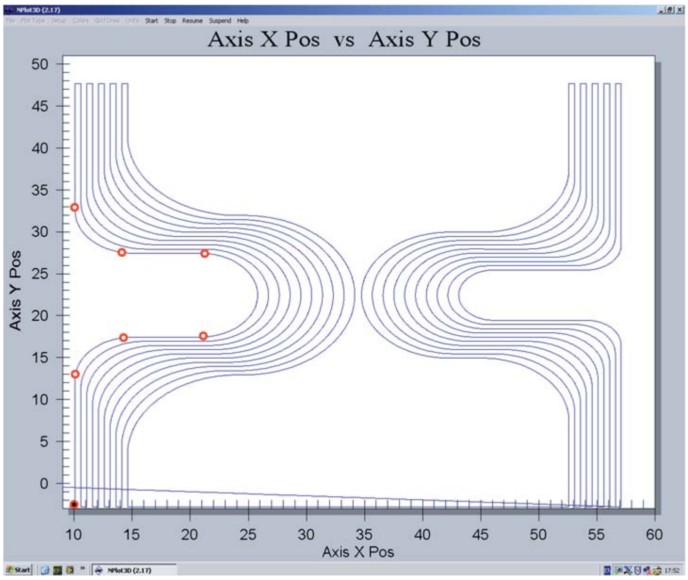
Waveguide lossses

Treasure map



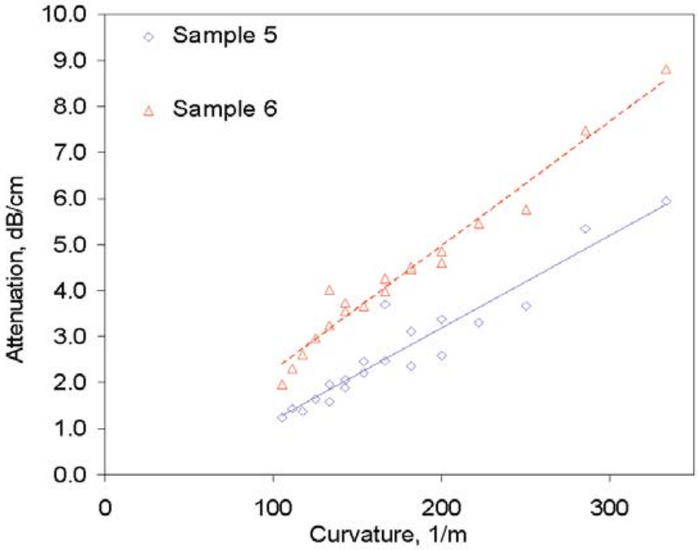
Optimal regime is an island in energy – translation speed plane.
Propagation losses of optimal waveguides are found to be about
0.1 dB/cm @633 nm and 0.5 dB/cm @1550 nm

Bending losses. Tracks



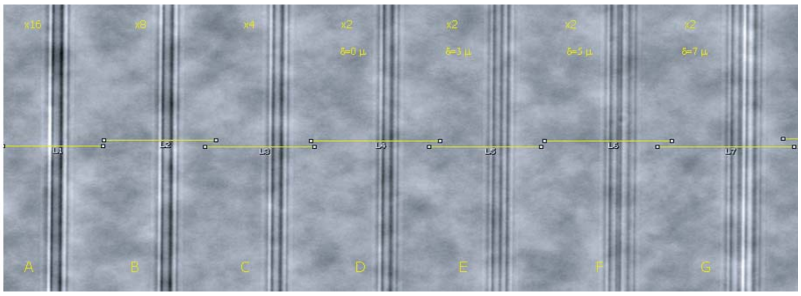
Optimal inscription regimes were exploited to manufacture **curved** tracks. All the tracks are designed to have the same length and comprise straight stretches and 4 arcs with different directions and curvatures.

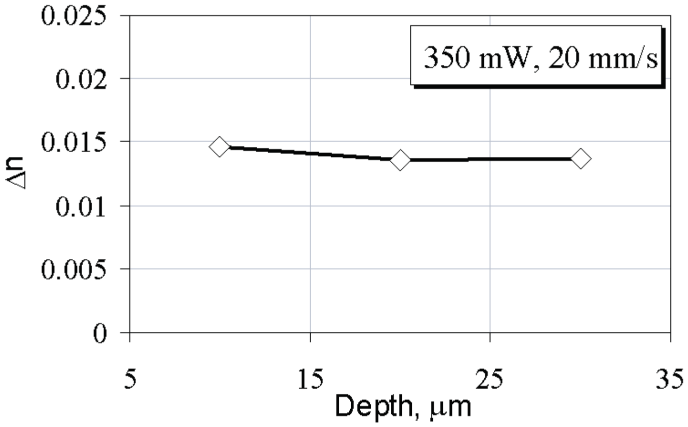
Bending losses. Measurements



Bending losses of optimal curved tracks compare to those of fibres and are now suitable for applications in integral optics.

Shallow and multiscan waveguides





Ref. index vs depth

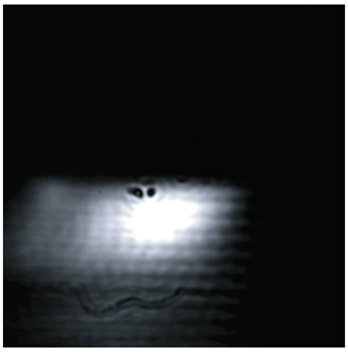
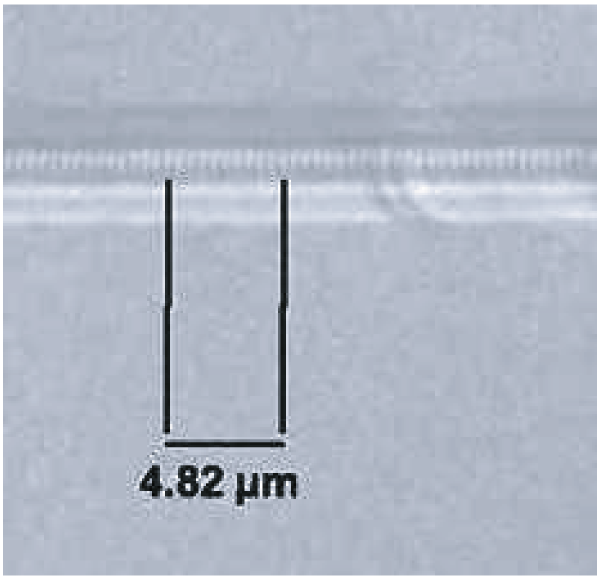


Image of near field mode

FBG structure embedded in fs inscribed waveguide

Work in progress.



Pulse power of the beam is modulated to induce a visually perfect periodic structure.

Conclusions

- Operation regimes for microfabrication of waveguides suitable for application optics found.
- Curvilinear waveguides with acceptable bending losses are demonstrated.
- FBG structure embedded in the waveguide fabricated in a single process with fabrication of the waveguide.

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