

# Fabrication of Monolithic Add-Drop Filters in Pure Silica by Femtosecond Laser Writing

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## ABSTRACT

This paper will review the fabrication of monolithic integrated optical devices by laser direct writing with femtosecond pulsed laser sources, starting with the description of experimental procedures and optimal conditions to fabricate low loss optical waveguides, directional couplers, Y-junctions and first order Bragg gratings by point-by-point writing methods. Finally, the characterization results of a fully operational Add-Drop filter in pure fused silica substrate are described.

**Keywords:** add-drop filters, integrated optics, optical waveguides, laser direct writing.

## 1. INTRODUCTION

The fabrication of integrated optical devices relies mostly on processes that involve materials structuring using some sort of photolithographic and etching steps. However, alternative fabrication methods relying on laser direct writing processes have been employed for fabrication of optical waveguides. The first attempts were performed on germanium doped glasses and UV laser sources; these methods were employed mainly for wavelength selective components, such as Bragg gratings. J. Albert *et al.* [1] demonstrated the fabrication of a fully operational Optical Add-Drop Multiplexer (OADM) using UV inscribed Bragg gratings on the arms of a Mach-Zehnder interferometer (MZI). More recently, K. Davies *et al.* [2] demonstrated the possibility to permanently modify the refractive index of glasses using non-linear absorption processes resulting from exposure to femtosecond laser pulses. Relatively to the first demonstrations of laser direct writing processes with UV laser sources on doped materials, the fabrication with femtosecond laser sources has a few advantages: do not require linear photosensitivity and therefore permits fabrication on mostly transparent optical glasses, allowing also 3D fabrication with very high spatial resolution (which is inherent to the non-linear absorption process).

This paper reports on the fabrication of a monolithic OADM entirely fabricated with laser direct writing with femtosecond laser radiation. This paper demonstrates the fabrication and the characteristics of the mostly important individual components typically required for demonstration of complex functional devices; these include low coupling/propagation loss waveguides (including low bending losses), directional couplers with controllable splitting ratio, efficient Bragg grating written by point-by-point techniques, etc.

## 2. EXPERIMENTAL PROCEDURE

The fabrication of integrated devices in pure silica substrates by the femtosecond laser writing transversal method employed, Fig. 1, relies on 2D sample movement using X-Y Aerotech air bearing stages (ABL10100-LN) and vertical beam spot positioning by a piezo writing lens stage (PI Instruments PIFOC PI-725).

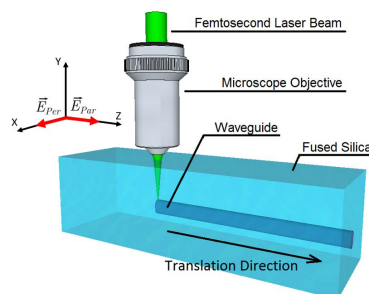


Figure 1. Femtosecond laser fabrication by transverse methods.

The home-assembled laser writing machine allows sample positioning, beam visualization, polarization control, beam expansion and power control using in-house developed software. The writing machine is coupled to an Amplitude Systèmes Satsuma HP fibre amplified femtosecond laser system emitting 250 fs laser pulses at 515 nm (second harmonic). In all results presented in this paper the pulse repetition rate was set to 500 kHz and the laser beam was focused inside the substrate by an aspheric lens (NA = 0.55). A train of laser pulses can be

obtained by driving the laser internal acousto-optic cell by a function generator (Stanford Research Systems DS345). The laser writing apparatus is pictured on Fig. 2.

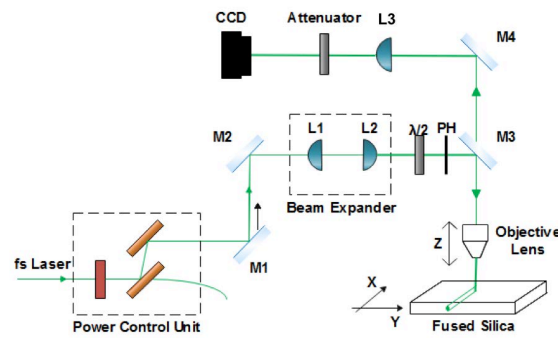


Figure 2. Schematic representation of laser writing apparatus.

The fabricated devices are facet polished after laser writing and characterized in terms of losses, mode profiles, wavelength dependency using a tuneable laser source (Santec TSL-210V), white light sources, optical spectrum analyser, optical detector (EXFO Optical System IQ 203 with IQ 1600 modules). When tested with bare fibers index matching fluids are used (Cargille AA series). Functional devices employ V-groove fiber array blocks (Precision Micro-Optics) with 250 μm pitch, which are subsequently glued with Norland Optical Adhesive 61 and using an ultraviolet source (Hamamatsu LC8).

**3. EXPERIMENTAL RESULTS AND DISCUSSION**

The schematic of the OADM filter is represented on Fig. 3.

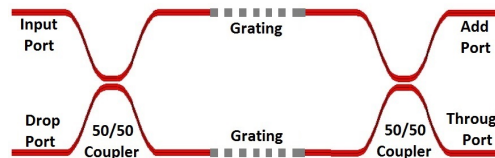


Figure 3. Schematic representation of integrated OADM based on symmetrical Mach-Zehnder interferometer.

The first objective is to determine the best writing conditions to write low loss waveguides followed by a demonstration of a toolbox of fundamental components necessary to build more elaborate functional devices.

**3.1 Low Loss Waveguides and S-Bends**

The fundamental building block of any high performance device is low loss waveguides, so the first tasks were to determine the processing conditions that resulted in the best waveguides. The fabrication parameters tested were: laser pulse energy, writing beam polarization, depth and scanning velocity. The best processing conditions that resulted in low loss waveguides at 1550 nm were obtained with 250 nJ for waveguides written 50 μm below the surface at 400 μm/s and using longitudinal polarization (aligned with the scanning direction), Fig. 4a. The S-bends were investigated by changing the lateral offset between 125 μm and 500 μm, which corresponded to a maximum radius of curvature between 3 mm and 80 mm. The results obtained show that the excess loss at 1550 nm becomes negligible for radius of curvature above 50 mm, Fig. 4b.

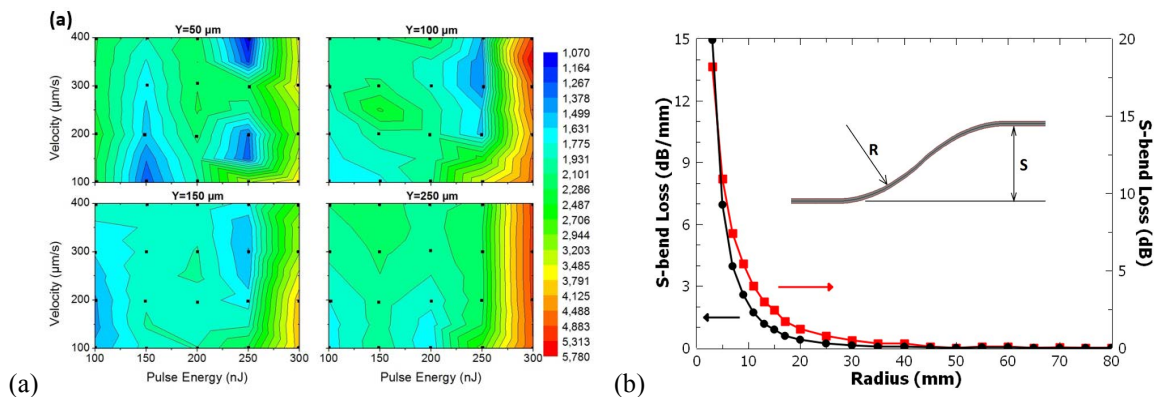


Figure 4: (a) Insertion loss of linear waveguides at 1550nm (in dB); (b) S-bends excess loss due to curvature.

### 3.2 Directional Couplers Design

Power splitters are also an important blocks of the fundamental components toolbox. Using the data from the radius of curvature from previous section, power splitters based on directional couplers were demonstrated. The results are resumed in the results of Fig. 5. It was found that for waveguide separations above  $7.5 \mu\text{m}$  in the coupling region, the total insertion loss was compared to that of a single straight waveguide. Also, multiple devices fabricated targeting 3 dB power splitting devices shown a good control over the fabrication process.

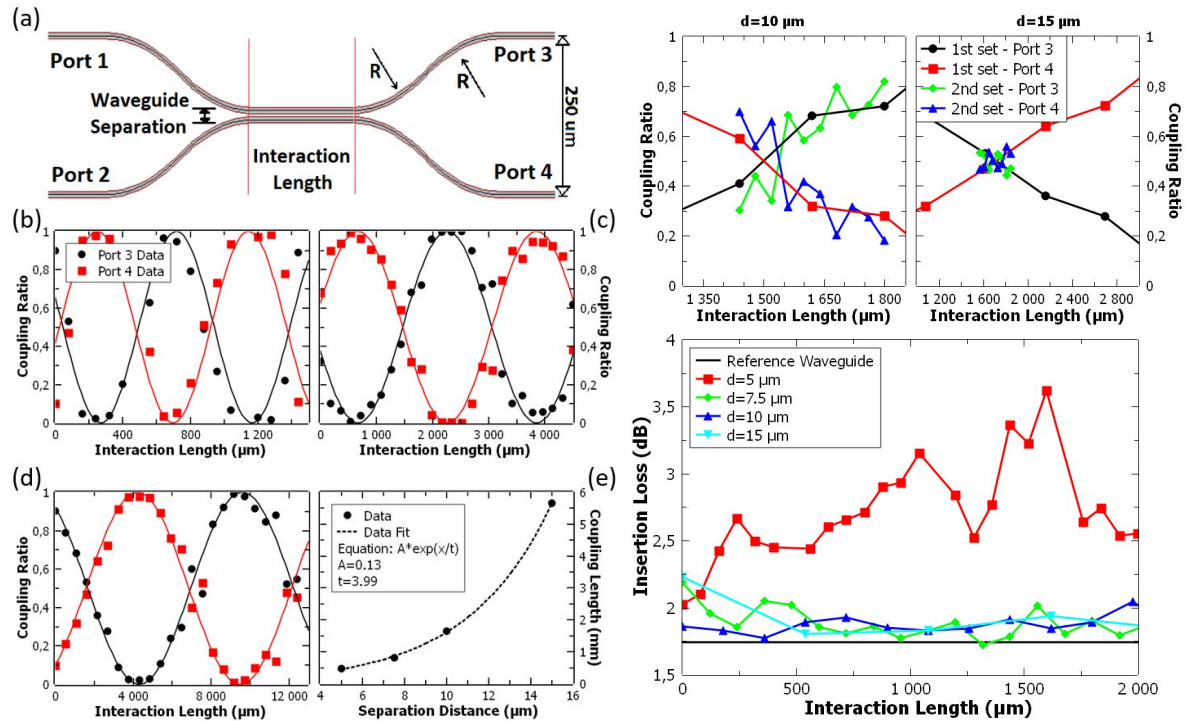


Figure 5. Coupling ratio and insertion losses of directional couplers written with different arms separation.

### 3.3 Bragg Gratings Fabrication

The fabrication of an OADM filter based on a Mach-Zehnder relies on the filtering properties of Bragg gratings written symmetrically on the arms of the interferometer [3]. The exposure to train of femtosecond laser pulses can be achieved by modulating the writing beam during exposure. Since femtosecond laser exposure has a very high spatial resolution, first order Bragg gratings can be written either on optical fibers or planar devices (the main difference is that on standard SMF-28 optical fibers, for example, the gratings are written on a pre-existing core while in pure silica substrates we are speaking of a Bragg waveguide grating – BWG). The Bragg wavelength is proportional to the grating period, which is given by the value of the scanning velocity over the frequency of the modulated laser beam.

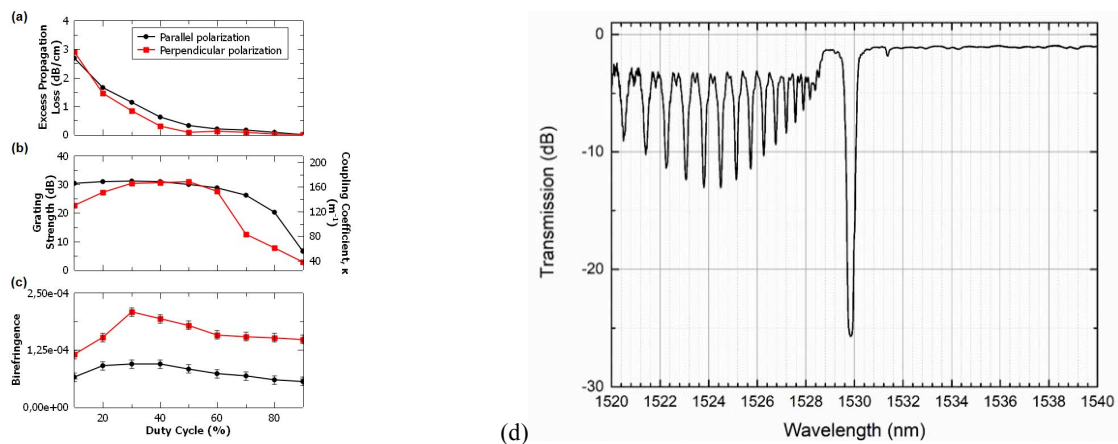


Figure 6: (a) Excess propagation loss; (b) Grating strength; (c) Birefringence as a function of the modulation (square) wave duty cycle; (d) Bragg grating in a standard SMF-28 optical fiber ( $L = 10 \text{ mm}$ , written at  $200 \mu\text{m/s}$  through an oil immersion objective with  $NA = 1.25$  and  $40 \text{ nJ}$  pulses with a square modulation function with 50% duty cycle).

The objective was the fabrication of Bragg gratings with central wavelength close to 1550 nm by fabricating structures with a period of 536.1 nm (zero order gratings). As shown in Fig. 6 there is a trade-off between loss, grating strength and birefringence in respect to the duty cycle of the laser modulation function; a 60% duty cycle results in high strength gratings ( $\approx 29$  dB) and relatively low excess loss ( $\approx 0.3$  dB/cm). However, a duty cycle of 40% and parallel writing polarization was chosen for Bragg grating fabrication on the OADM in order to ensure stronger gratings.

### 3.4 OADM Fabrication

The OADM was written in a 75 mm long fused silica substrate by assembling straight input/output sections, S-bends, directional couplers and Bragg waveguide gratings (BWG). The total fabrication time was around 13 minutes and the final length after polishing was 54 mm (28 mm for directional couplers, 20 mm for the BWG's and the remaining was straight waveguides connecting the other elements). After polishing the V-groove fiber array blocks were aligned and glued. Figure 7 shows the measured reflected and transmitted spectra of the final assembled device.

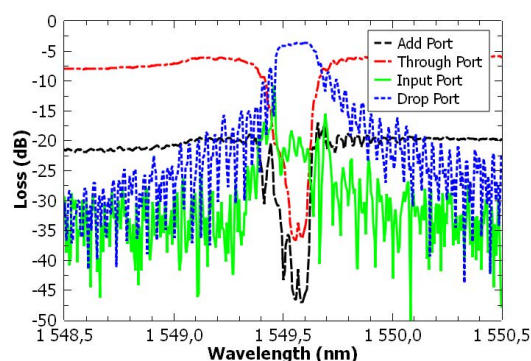


Figure 7. Measured spectra at the different input/output arms of the OADM.

The fabricated Bragg grating had an isolation better than -30 dB with a 3 dB bandwidth of 0.19 nm and with a side lobe suppression of 20 dB for  $\Delta\lambda = \pm 0.75$  nm. A total insertion loss of 4.9 dB and 3.7 dB was recorded on the through and drop ports, respectively. The results presented here were obtained in a device *as fabricated* and therefore no optimizing techniques were employed; these could include correction of phase balance using laser trimming or reduction of grating birefringence dependence [4], for example. Also, the Bragg gratings had uniform modulation and therefore there is still room for improvement by employing techniques such as grating apodization for enhanced crosstalk.

## 4. CONCLUSIONS

The fabrication of a monolithic integrated optical OADM fabricated entirely by laser direct writing using a femtosecond laser is reported. The device consisted on two Bragg gratings written symmetrically in the arms of a Mach-Zehnder interferometer. The non-optimized device exhibited a 3 dB bandwidth of 0.19 nm with a -30 dB and -20 dB for intra-channel and inter-channel crosstalk, respectively.

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