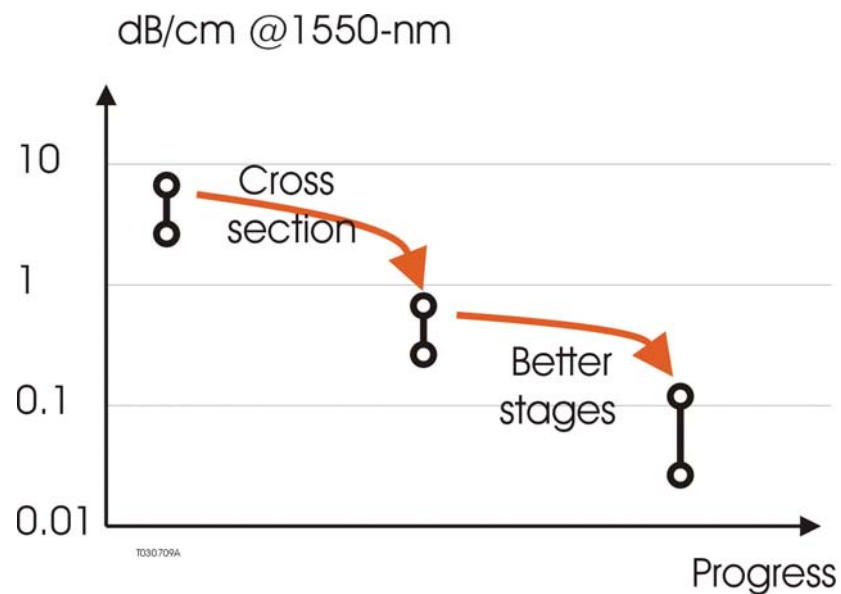


Translume

MANUFACTURING OF HIGH QUALITY INTEGRATED OPTICAL COMPONENTS BY LASER DIRECT-WRITE

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Manufacturing of High Quality Integrated Optical Components by Laser Direct-Write (M103)

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Abstract

The index of refraction of most glasses can be permanently changed by exposure to femtosecond laser pulses. This effect can be quite strong, allowing for the fabrication of various two-dimensional or three-dimensional light guiding structures. Passive optical waveguides, splitters, couplers, and long period gratings, have been manufactured using this femtosecond direct-write technique. Active waveguides have also been produced with this method.

We describe recent work at Translume in femtosecond direct write to produce waveguide-based devices characterized by low insertion loss and low birefringence. Performance data, including optical characteristic and environmental test reliability, is presented.

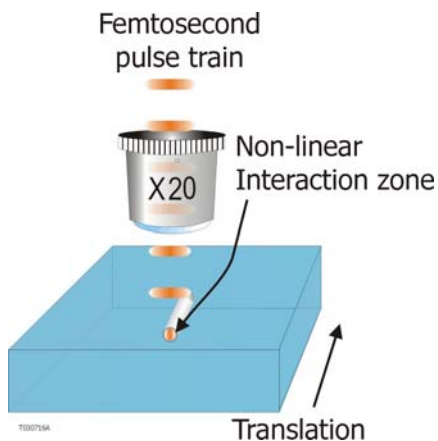
Glass/UV-light Interaction

The properties of glass can be changed by exposure to UV light. This effect is generally weak, but the photosensitivity of many glasses can be significantly enhanced with the proper doping.

As early as 1978 Hill *et al.*¹ created permanent gratings in an optical fiber using this effect. Since then, this discovery has had a major commercial impact on the telecommunication industry. UV lasers (continuous-wave or nanosecond pulsed) are routinely used to machine devices incorporating some type of Bragg gratings. These devices are used in fiber communication systems for gain flattening, wavelength selections, multi-wavelength pump combiners, Raman filters, compensation of group-velocity dispersion, etc.

Femtosecond Waveguide Writing

A related process is based on near-infrared femtosecond (fs) to construct optical waveguides and other optical structures in glass.^{2,3} The process can either be serial or parallel,⁴ although the former approach is the most common. Numerous passive waveguide structures such as splitters,⁵ couplers,⁶ delay lines, MZI, and long period gratings⁷ have been demonstrated using the femtosecond process. Active devices such as variable optical attenuators, thermo-optic switches, thermo-optics filters, and gain blocks⁸ have also been demonstrated.

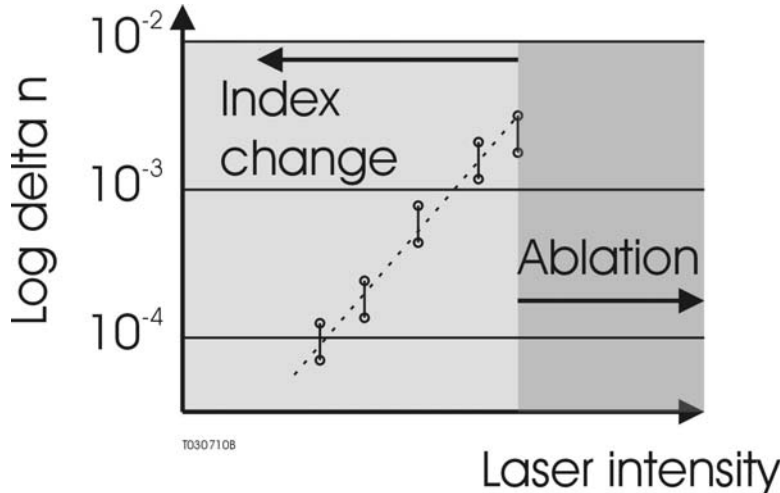
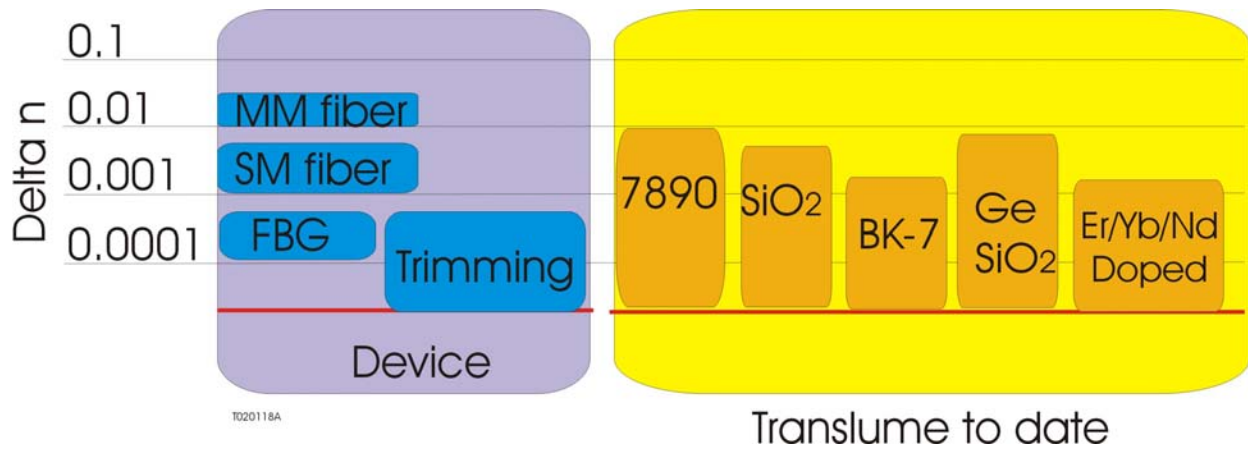


In contrast to the UV-based process used in the manufacturing of FBGs, the femtosecond laser process (femtoWrite™) does not require photosensitized glasses.

Linear absorption between near-infrared light most commonly associated with femtosecond sources and transparent glass is negligible since the absorption edge for most glass is in or near the UV. However, the very high intensities associated with focused femtosecond pulses enable non-linear absorption through multiphoton processes in all glass compositions. Femtosecond absorption induces material changes to the substrate glass, creating an index change.

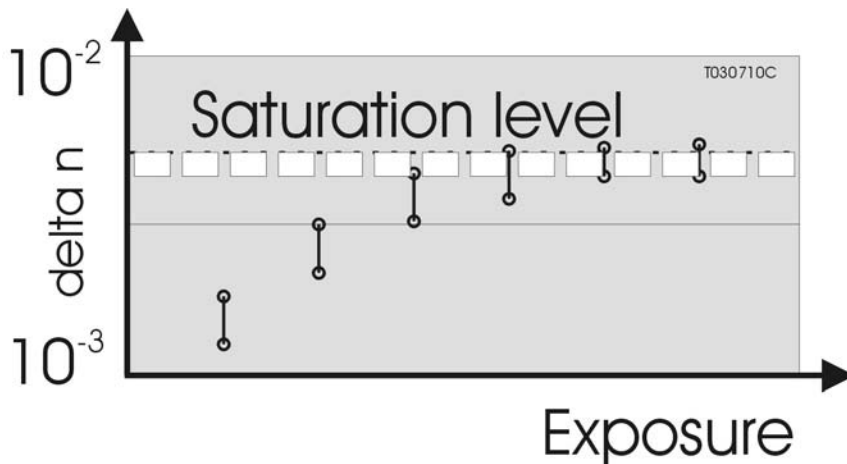
A full understanding of the processes behind this change in index of refraction is still lacking.⁹ However it is fair to say that there are mounting evidences that various mechanisms are at play and that their respective importance is a function of the glass composition.¹⁰ In any case, the index changes generated with the femtoWrite™ process are significantly stronger than that typically encountered in the UV-laser manufacturing of FBGs: Femtosecond laser induced index changes of up to several percents have been reported in some glasses.³ At Translume we have not been able to go past the 1 % index change mark. This is however sufficient to manufacture various two-dimensional or three-dimensional light guiding structures of commercial interest.

Our best results have been obtained in fused silica (doped or undoped) and in Corning composition 7890 as shown below. [The delta n, *i.e.* the difference in index of refraction between the bulk and the core of the waveguide, were measured with near-field refractometer]



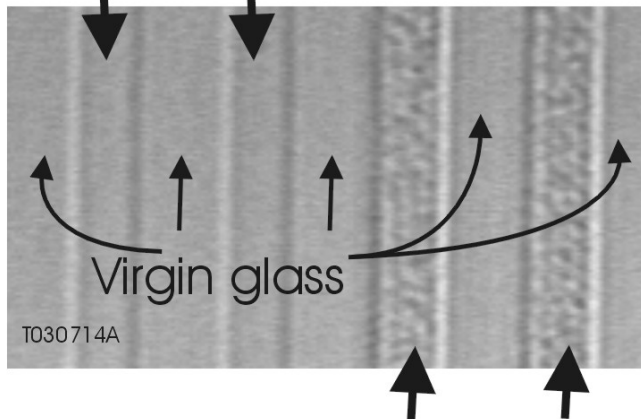
For all glass compositions tested the change in the index of refraction is a function of the laser illumination. The exact relationship between the laser intensity and the delta n is a strong function of the glass composition. Fused silica has one of the simpler dependence (see illustration on left).

Exceeding a well-defined threshold result in ablation of the glass rather than index change.



For SiO₂, multiple laser exposures (at a given laser intensity) will progressively raise the corresponding delta n until it reached a saturation value. Other glasses show a similar behavior.

Zones incubated



Pre-exposing the glass with low intensities pulses can raise the ablation threshold

Zones not incubated

Optical Performances

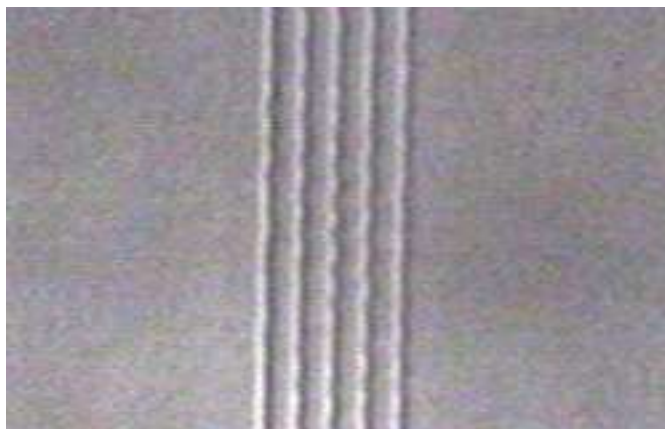
The main optical parameters characterizing a waveguide are size, delta n, optical loss, and birefringence. The size and the delta n of a waveguide are related to its ability to support guided propagation of light of a given wavelength in a single mode or multimode fashion. These parameters also govern bending loss as function of the radius of curvature. (A waveguide with a weak delta cannot turn sharply without substantial loss.)

Optical Parameters-Loss:

Optical loss (or lack of) is important to any optical device and is a critical parameter in the telecommunications field. Several mechanisms contribute to the loss budget in a typical optical device: absorption loss, scattering loss, mode-mismatch loss, etc.

We have found experimentally that absorption losses are not a significant issue in the visible or the near infrared when manufacturing devices out of SiO₂.

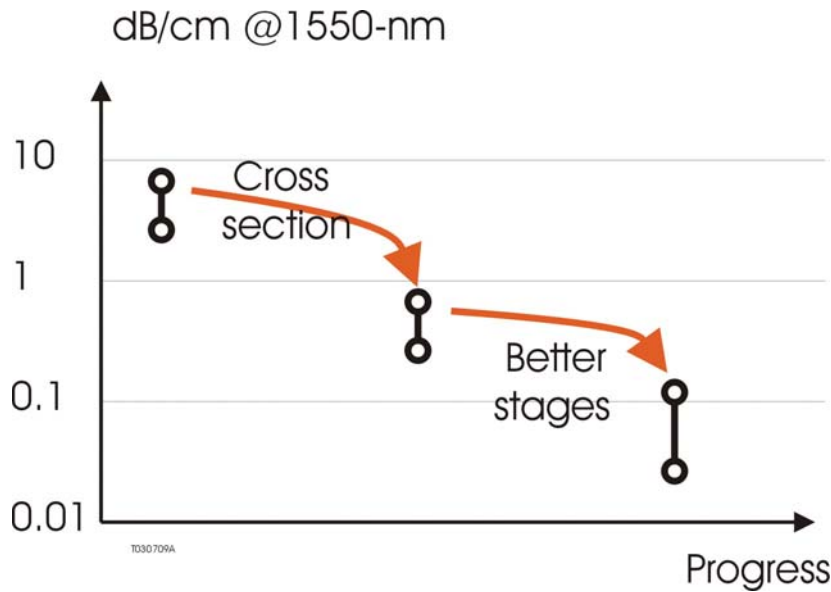
In contrast, scattering losses can be quite severe. Strong scattering centers are created when the femtosecond laser intensity exceeds a threshold value for bulk ablation. Working consistently below the ablation threshold eliminates this source of scattering.



Waveguide sidewall modulation resulting from a non-uniform translation of the femtosecond laser beam during the writing process also creates scattering centers. This scattering loss factor becomes significant when the side modulation is of the order of a quarter of a wavelength. Periodic modulation further enhances this problem.

This loss factor can be drastically reduced using high-quality stages in the manufacturing process.

Finally in order to guide light efficiently optical waveguides must have a certain minimum cross-section. This minimum value is function of the delta n – the larger the delta n, the smaller the minimum cross-section can be. If the cross section falls below this minimum value, the waveguide will “leak” light. The loss associated with this phenomenon can be extremely high.



Having addressed these issues we now manufacture single-mode 1550-nm waveguides in SiO₂ with loss as low as 0.04dB/cm.

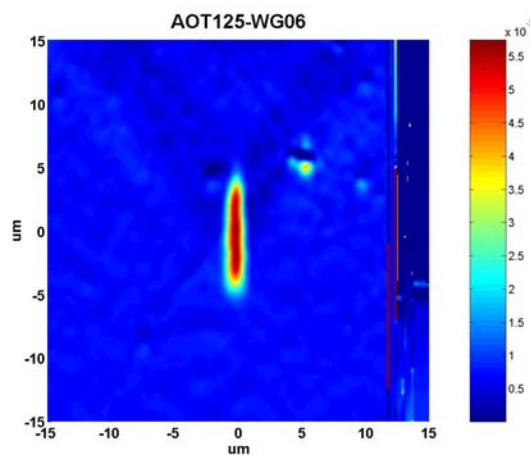
Note that additional loss factors are present each time the waveguide reaches a material interface.

Optical Parameters–Birefringence & Polarization

Optical devices are generally designed to either show strong polarization dependence or to show no polarization dependence. Several factors – form, stress, and material - can influence the polarization response of a waveguide. With our femtoWrite process we can control the form (cross-section) and the local stress birefringence, thus creating waveguides and waveguide assemblies that exhibit well-defined polarization dependence.

Polarization dependence and form-factor

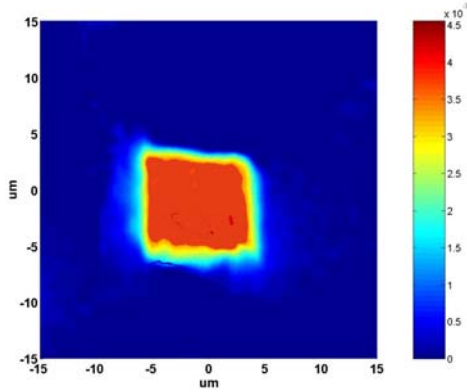
The form of a waveguide (*i.e.* its cross-section) will affect its response to polarization. A rectangular or elliptical waveguide will generally show a polarization preference, while a waveguide with a round or square cross section will not show a polarization preference (assuming the absence of stress or material birefringence).



A laser beam focused with conventional optics has an intensity distribution that is shaped like an ellipsoid.

A waveguide manufactured with this type of focusing setup will have an elliptical cross-section. Experimental data confirms this, as shown in the accompanying index map on the left.

Waveguides with this kind of cross-section exhibit strong polarization dependence.

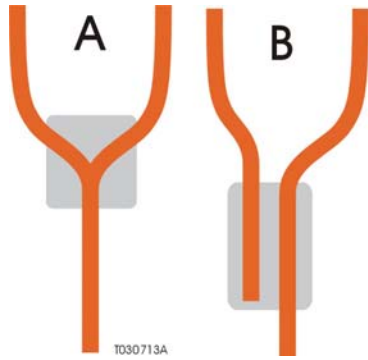


On the other hand, a waveguide with a round cross-section or square cross section will show very little or no polarization dependence (in the absence of stress or material birefringence).

Shaping of the cross-section can be achieved through various processes including laser beam shaping.

Polarization dependence and stress birefringence

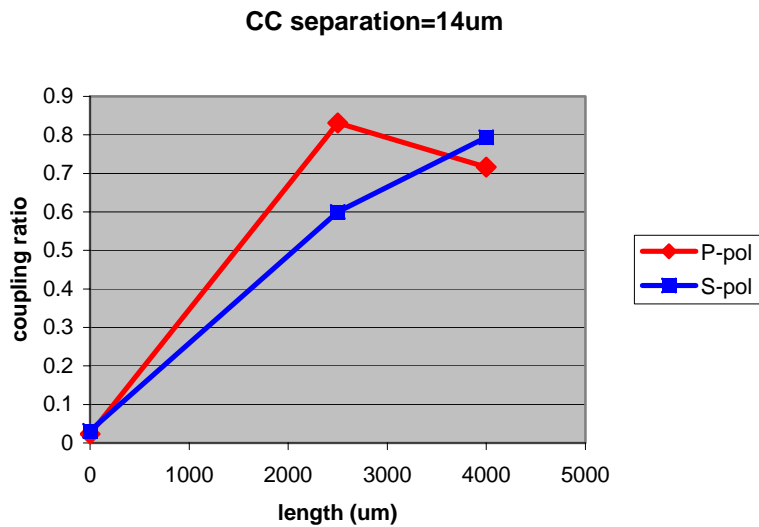
Polarization dependence can also be introduced through material or stress birefringence. Glasses, being amorphous, have no natural material birefringence. However the index change process itself can result in the creation of local stress birefringence.



Low-level birefringence is often best seen in Y-couplers (A) or evanescent couplers (B).

(The gray areas are zone of high sensitivity to stress birefringence.)

Fused couplers show less polarization dependence



We have found it quite difficult to manufacture waveguides that exhibit a total absence of stress birefringence. The residual stress birefringence associated with our femtoWrite™ process as it stands today is of the order of 1/100 to 1/10 of the induced Δn . Fortunately there are few applications where the waveguides must be completely free of birefringence. If required, operating the device with a single polarization can eliminate stress birefringence effects. To that end we have developed device front end sections that act as polarizer.

Environmental Stability

Good optical quality is not the only requirement of concern. The resulting devices must also be robust. They should be able to be stored under a range of environmental conditions.

High temperature tests

We have tested waveguides we manufactured in fused silica under progressively higher temperatures. The waveguides were found to be extremely temperature resistant

Manufacturing Yields

The percentage of good devices is often low in optical component manufacturing. Consequently the optical component industry has adopted several post-processing techniques to improve yields: one of the most commonly used yield-improvement technique is “trimming”.^{11,12,13} Trimming refers to active adjustment of device parameters during and after the initial waveguide manufacturing.

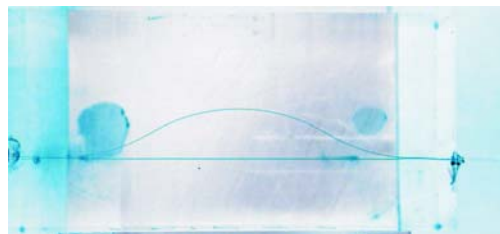
Real-time Monitoring and Feedback

In sharp contrast to lithographic-based planar technology, the femtoWrite™ process is conducted in open manufacturing cells – no vacuum or high-level cleanroom is required. This environment allows real-time monitoring of the device being manufactured, which when combined with real-time feedback can be used to actively compensate for individual component differences.⁷

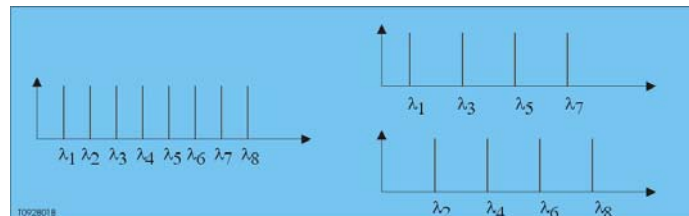
Device Tuning

Once the device initial exposure is complete, the device can be tested and then slightly modified with additional fs laser exposure to “tune” it. The process of index of refraction modification is somewhat cumulative, which allows for the fine-tuning of the index of refraction.

The ensuing yield advantage associated with the femtoWrite™ process is best illustrated when manufacturing interferometric devices such as the 50-GHz interleaver shown to the right.

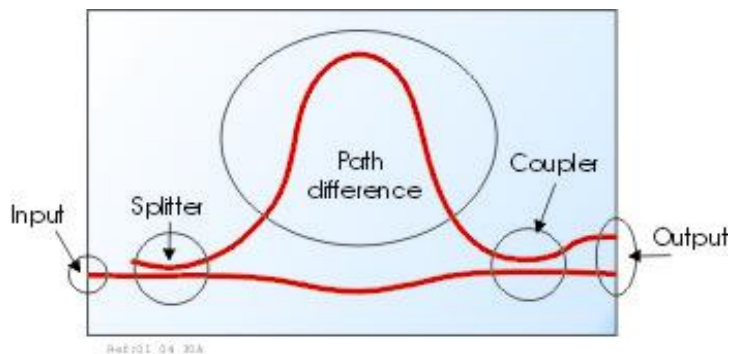


Interleavers are used in telecommunication networks to separate or combine signals of various wavelengths

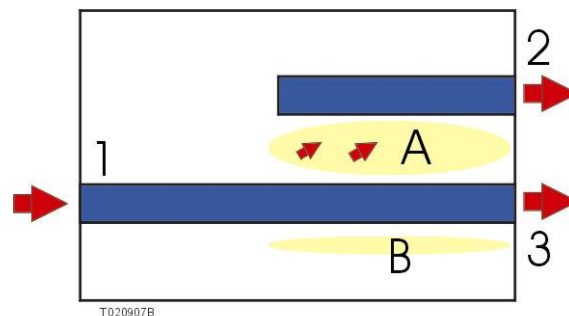


An interleaver includes at minimum one splitter, one coupler and one pair of arms of different length.

Any variance when manufacturing these key elements will affect the overall performance of the interleaver.



For example, the splitter must provide a well-defined energy splitting ratio between its two outputs. If the splitting ratio departs from the design value, the device “contrast ratio” will suffer. The exact splitting ratio can be controlled through trimming.

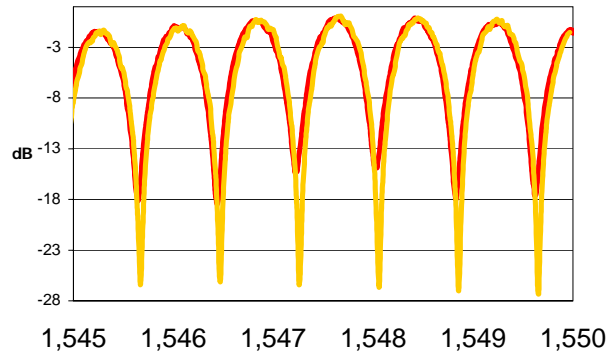


Raising the index of refraction in region “A” will enhance the energy transfer from port (1) to port (2). In contrast raising the index in region “B” will increase the energy output at port (3).

Correcting the splitter ratio can drastically improve the isolation between adjacent channels as shown on the right.

Red = isolation prior to trimming;

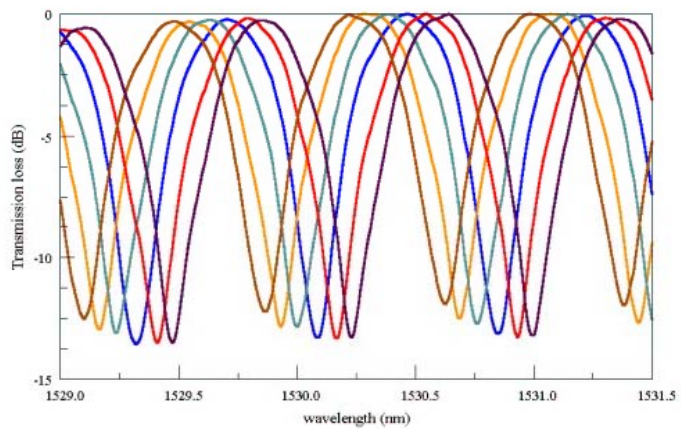
Orange = isolation after trimming.



Trimming the optical path difference between the two arms of an interleaver provides a way of centering the device on the international wavelength grid (ITU grid).

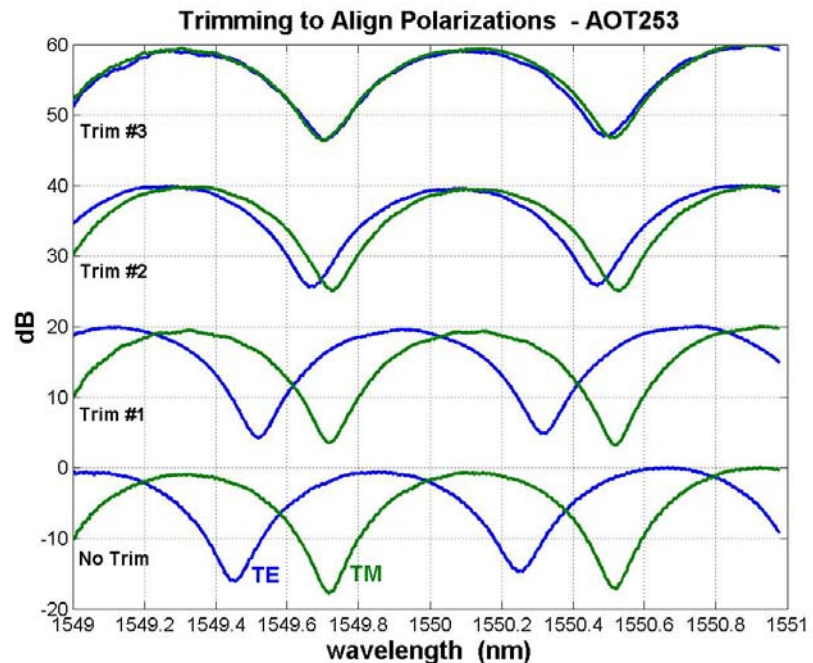
For a high quality long haul device the optical path-lengths must be accurate to a few tens of nanometers over the full length of the device. This is a very stringent requirement, which drastically affects the manufacturing yield of good devices.

Note that we do not change the geometrical path difference, but rather we work with the optical path (*i.e.* geometrical path times the index of refraction) through a minute change (10^{-6}) in the index of refraction.



Similarly one can correct for excessive polarization dependence.

Note that the TE response was progressively corrected without affecting the TM response. This is a highly desirable characteristic of our process.



Conclusion

- We have shown that our femtoWrite™ process enables high yield manufacturing of lightwave circuits through:
 - An inherently controllable manufacturing technology;
 - In-situ monitoring and testing;
 - Post manufacturing tuning
- Improving on previous work, waveguide loss per centimeter has reached acceptable limits for demanding integration goals,
- Birefringence can be controlled to levels no previously achieved.

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