Invited paper (European Materials Conference – Strasbourg – June 99)

Integrated optics based on organo-mineral materials

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New technologies based on organic-inorganic materials are shown to be very flexible, while they present interesting performance. The process needs only four steps, and the local refractive index change necessary to guide light may be imprinted with a simple UV exposure. Several solutions are given to design basic structure of guides and hence to make optical circuits which cover the domain of power splitters to wavelength division multiplexers, including directional couplers, gratings… Also optical amplification is shown to be possible, and the connection problem is tackled.

Keywords : Integrated optics, organo-mineral material, sol gel process, optical waveguides

Introduction :

The expansion of telecommunication networks has induced the development of optical links using optical fibers. Integrated Optical Circuits (IOC) are imagined to solve various problems in routing, dividing, filtering the signal, and to reduce the number of electronic-optic interconnections. Presently various integrated optical circuits are developed with different materials and technologies: III-V semiconductor or silica with photolithographic process, silica-on-silicon with flame hydrolysis deposition (FHD), or chemical vapor deposition (CVD) including variants like plasma enhanced (PECVD) and thermal diffusion of dopant (esp. Ti) through the surface of a lithium niobiate crystal. Passive devices such as 1 x 4 and 1 x 8 power splitters elaborated by ions exchange in glass are already industrialized. The connection with optical fibers ("pig-tailing") is obtained through an active process which remains expensive. No process, is presently outstanding enough to justify a domination on the market in the fabrication of complex IOC.

A technology, based on the sol-gel process is used to make vitreous layers for various applications, and in particular in optics [1]. This process is based on the mixture of liquid precursors (generally alcoxides) which make a gel (mineral network) at room temperature under the action of water. The deposition step uses inexpensive equipment such as dipping or spinning. After a drying step followed by a densification one, high quality films of various oxide glasses can be achieved. This pure mineral material however is limited to the fabrication of thin layers not adapted to the dimensions of single mode fibers [2].

Polymers are an alternative : thick layers can be made, and their price is reduced. Their basic refractive index can be adjusted, and a slight local change of index can be used to print an optical circuit. Also, the polymerization allows a selective etching of the layers. These materials however suffer from aging problems, poor mechanical resistance and need a low temperature functioning environment.

A new way is the combination of the mineral sol-gel process and the polymer networking. The advantages of both technologies may be combined by an adjustment of the part of each. This kind of material receives an increasing attention because of its mechanical, optical and physical properties, it can be largely adjusted between a mineral and an organic behavior. The low temperature process enables to mix organic precursors to the sol-gel precursors to develop new materials called organic-inorganic or hybrid.

In the second section, we present different fabrication processes of organo-mineral materials, in section three the qualities of the material and structures of guides which can be made with these materials. The fourth section is devoted to the several passive devices made with these structures. Perspectives conclude this presentation.

Fabrication

First organic-inorganic three dimensional (3D) waveguides were developed by Krug & al. in 1992 [3]. The process was improved since 1994 by a collaboration between Najafi's team from Ecole Polytechnique of Montreal and Andrews's team from the Mc Gill University of Montreal [4]. More recently, because of the process simplicity, of the high performance obtained for waveguides, of the complexity of IOC which can be made, the number of researchers working on this material is booming [5].

The more advanced devices are made by mixing two organic-inorganic precursors: methacryloxypropyltrimethoxysilane (MAPTMS) and the reaction product between the zirconiumIV-n-propoxide and the methacrylic acid (Zr(OPr)4:MAA)[6]. This mixture is able to make a mineral and an organic network as illustrated in figure 1. The mineral network is obtained through the hydrolysis and the polycondensation of alcoxide groups. The organic network is created by the polymerization of double bonds under UV action.

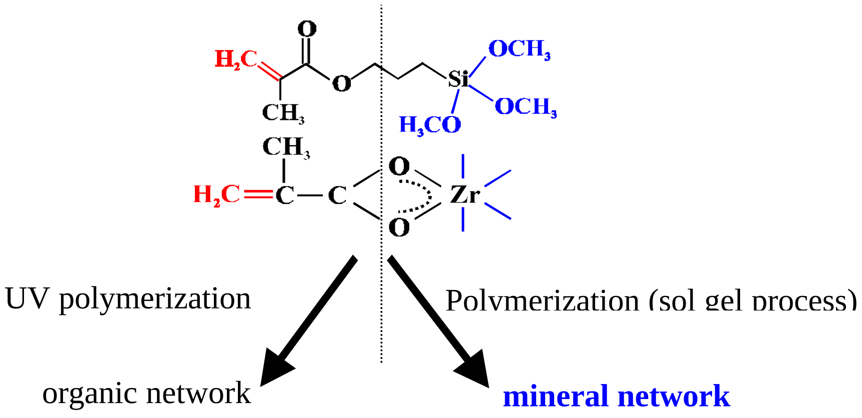

Figure 1 : Composition of organic-inorganic material

The basic process consists of four steps : material synthesis, layer deposition, circuit printing and thermal stabilization.

A x molar quantity of MAPTMS is hydrolyzed by a 3x/4 aqueous solution of HCl (0.01N). A y quantity of $Zr(OPr)_4$:MAA is then added. After another 5x/4 water introduction, the photoinitiator is added. The solution with the x:y composition is then deposited by dip or spin coating and dried at a temperature high enough to give mechanical stability associated to the mineral network formed, but as low as possible to have an optimal UV polymerization (on the organic part). A good compromise consists of a 30 min prebake at 70°C.

The layer is then exposed under UV light through a mask with the desired pattern, other possibilities of local exposure have been experimented also : interferometric patterns for gratings [7], laser direct writing for optical circuits [8]. The UV polymerization process, presented in figure 2, induces both a refractive index increase (Δn until 0.025) and a reasonable resistance to alcohol attack. The set-up uses a 400 W UV mercury lamp emitting at 365 nm. At the end of the process, the device is baked at 120°C for 1 h to definitely stabilize the structure by enhancement of the mineral network.

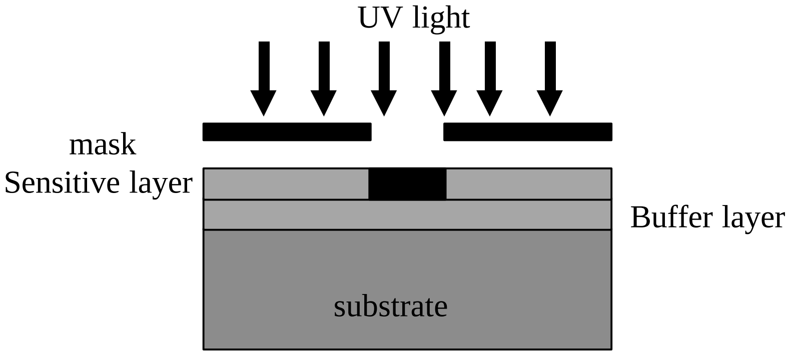

Figure 2 : Example of circuit printing using a mask in an organic-inorganic layer.

Qualities of the organo-mineral layer

The sol-gel process was for long time seen as a process limited to the fabrication of very thin layers : now, with organic-mineral material, a layer, deposited by dip-coating or spin coating, can be adjusted between 2 µm and several tens of microns. This is an important point, for several applications, like insulating layers, coupling for clock distribution, connection with single mode or multimode fibers, sensors…

The basic index can be as low as 1.46 using silicate precursors, and can be much higher using aluminates, zirconates or titanates…It can be precisely adjusted to the values encountered in plastic or silica fibers, thus limiting the excess coupling losses due to reflections.

Within this index range, the local index change can be selected between 0.0001 and 0.03 by ultraviolet polymerization of the organic part, and up to 0.05 by layer stacking. Through local etching after UV polymerization, the index change can be as high as 0.5 (index change between the material and air).

The mechanical properties i.e. scratch resistance, relative thermal resistance are due to the presence of a mineral network. Those properties increase with the ratio of the mineral part. A good trade-off can be chosen when considering the envisaged application.

The polymerization is depending mainly on the presence of a double bond C=C, of a UV photon and a photosensitizer at the same time in the same place when the mineral network is not yet established. The absence of the photosensitizer can be used to make inert layers with the same index and mechanical properties as imprinted layers. These conditions can be easily controlled to ensure a reproducible process.

These layers can be deposited on many types of materials, including glasses, semiconductors, metal and other layers, either directly or with the addition of a tensio-active solution to improve the interfaces if necessary.

Structures

The flexibility encountered in the process allows the fabrication of a large variety of layer compositions. These layers can be combined to give various structures : from basic planar waveguides to buried waveguides including ridges, multi level guides, gratings… Figure 3 shows the main structures which can be made.

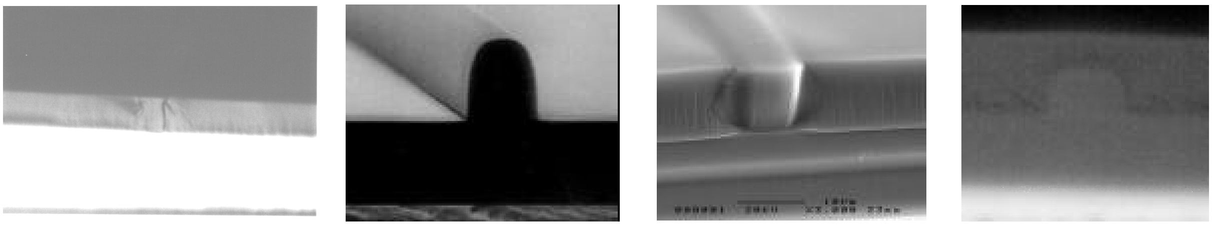

Figure 3 : Cross sections of various structures : a) planar , b) ridge, c) buried, d) covered ridge

Planar waveguides

The basic structure of a channel waveguide made from these organic-inorganic layers is presented in figure 3-a. It can be deposited directly on a glass substrate or on semiconductor substrate (like silicon). In this latter case, it is necessary to first deposit a buffer layer which can be made with the same technology, isolating the guide from the high index substrate. The silicon substrate with or without silica buffer layer, is a good candidate because of its crystalline structure : it can be easily cleaved inducing at the same time a good section of the supported layers, avoiding the need of polishing.

Ridge waveguides

Ridge waveguides (figure 3-b) are obtained by the etching of the non polymerized i.e. the non exposed parts of a sensitive layer. The etching is made by dipping of the sample in a solvent solution [9]. Actually, the organic network due to the polymerization makes the material not soluble. A buffer layer can be deposited prior to the deposition of the main layer, when the substrate index is high (i.e. silicon substrate).

Buried waveguides

Three methods can be used giving guides with different properties :

A coating can be deposited onto a planar waveguide, improving the symmetry of the structure, and of the electromagnetic field profile, which is better for propagation. Also, the nature of the coating can improve the mechanical resistance.

The protective coating can be deposited before the imprinting of the circuit. In this case, the guide is imprinted in the sensitive layer through the protective coating which is ultraviolet transparent [10] (Figure 3-c). This process enables to reduce the trapping dust during handling and the deformation of the guide due to the polymerization.

A quasi perfectly symmetrical section can be obtained through a variant : a ridge waveguide is buried under a protective coating of the same material as the buffer layer (Figure 3-d). The drawback is the difficulty to get etching with perfect smooth sides.

Stacking and crossing wave guides

Also multi level structures can be imagined with several guiding layers isolated one from the other by inert layers, as shown in figure 4-a. This is a way to reduce room in dense complex devices, or to make vertical directional couplers between guiding levels.

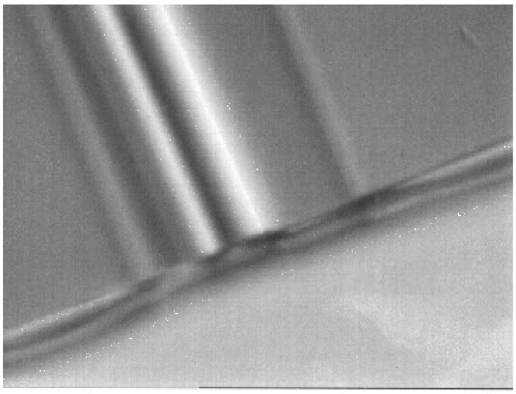

Figure 4-a : Multilevel structure

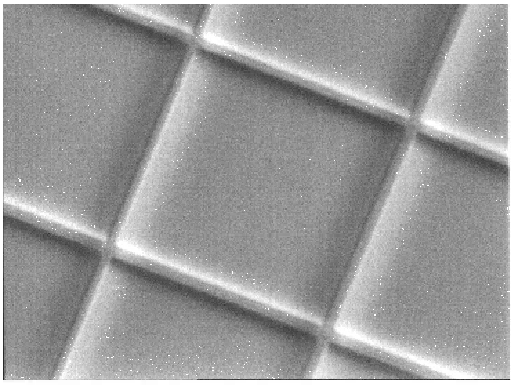

Figure 4-b : crossed guides

Crossed wave guides can be obtained by simple modification of the mask position. The direct imprinting allows a very precise definition of the crossing guides (see figure 4-b). This possibility increases the density of optical circuits. For crossing angles greater than 15°, the cross talk keeps a value less than –25 dB [12].

Laser direct writing

The UV exposure is conventionally performed through a mask using the well developed technology in microelectronics. An alternative which enables a very fast development of new circuits is the direct laser writing with a focused UV laser [8] such as Laser He-Cd or Ar.

Gratings

The two basic types of gratings are built on this type of material : index modulation gratings can be obtained with UV fringes of an holographic system [7], while relief gratings are built with phase masks, or conventional masks for long periods (greater than 1 µm) on slab or ridge waveguides [13].

Each different structure presents specific advantages which can be exploited depending on the envisaged applications.

Performance

The propagation losses are not only generated by the intrinsic absorption of the material, which is weak, but are also conditioned by the structure of the guide (thickness of the isolating layers, refractive index change, symmetry...) and the fabrication process (etching, mask, direct writing...). Besides the internal qualities, the coupling losses are usually maintained at a relative low value, this comes from the possibility to deposit thick layers (more than 8 µm) of hybrid sol gel materials : in accordance with the dimensions of single mode fibers.

Presently, the most used structure is the ridge guide because of the high index change and the induced possibility to make bent guides with small radii. At present, the best performance is obtained for buried waveguide made with a hybrid material; it is 0.1 dB/cm for propagation losses and 0.5 dB for coupling losses at 1.3 µm wavelength [14]. Propagation losses are measured by cut-back method [15], and coupling losses may be evaluated by the total insertion losses when the length of the guide is reduced to less than 2 mm long.

The fabrication is now sufficiently controlled to make singlemode waveguides for use at a fixed wavelength. An index change Δn of 0.012 to 0.015 between the buffer layer and a guide of 5µm x 5µm is controlled and allows to obtain singlemode guide at 1.3 µm and 1.55 µm respectively.

Optical circuits

Using this process, it is possible to imagine several IOC. Besides the straight waveguide, one simple device is the power splitter: 1 x 4 and 1 x 8 power splitter using Y-branches. These were made through the use of a mask and by laser direct writing. The functionality of this design of device does not depend on the guided wavelength. Figure 5 shows the output answer of a 1 x 8 splitter excited at 0.63, 1.3 and 1.55µm wavelength.

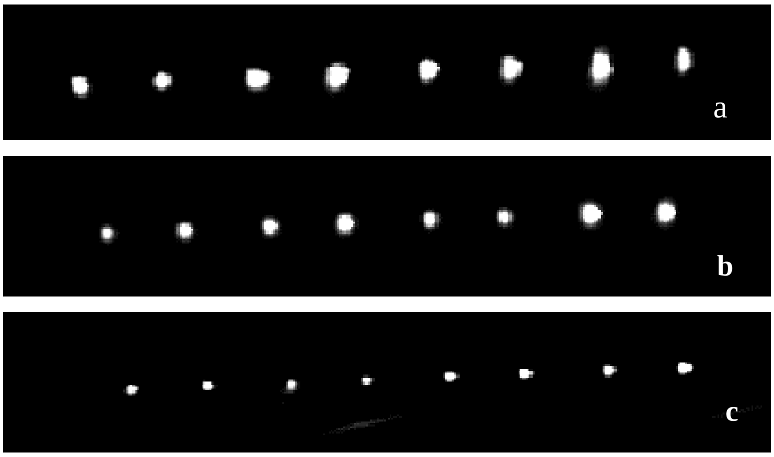

Figure 5 : Pictures at the output of 1x8 Y-branch power splitter at 0.63 µm (a), 1.3 µm (b) and 1.55 µm (c) wavelength

The guides are multimode at 0.63 and 1.3µm and become single mode at 1.55µm. No slab waveguide is excited because of the long radii of curve. A relatively homogeneous division is obtained at each wavelength. The insertion losses (16 dB at 1.3µm) are relatively important due to the length of this device (more than 2 cm) and to the losses in the Y-branches.

The flexibility of the material and of the structure is illustrated by the demonstration of directional couplers, also made by mask and direct writing, working at precise wavelengths for which they are designed. The mask consists of a set of nine X-couplers whose coupling lengths vary between 0 and 2 mm with a step of 0.25mm. In the coupling zone the parallel guides are separated by a distance of 6 µm. Figure 6 gives a top view of the device.

The couplers are tested at 1.3 and 1.55 µm wavelength. The relative power percentages at the outputs, for both wavelengths injected as inputs are given in figure 7 versus the coupling length. The coupling is a function of the wavelength, as predicted by the theory. This behavior induces many applications of this device, by modifying the coupling length. It can be used as wavelength router, balanced or not balanced power splitter, or wavelength filter. A near total coupling of the light can be obtained at 1.55 µm for a coupling length of 1.5 mm. These couplers can be used to separate two wavelengths such as 1.3 µm and 1.55 µm but if the wavelengths are too close, the coupling length has to be very large.

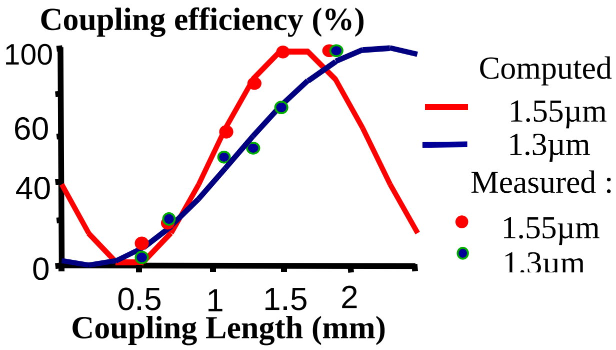

Figure 6 : Top view of directional couplers

Figure 7 : Coupling versus length

Another optical component which divides the power is the star coupler. Its behavior depends also on the wavelength, here to focus light on different directions. Figure 8-a shows a top view in which the resolution obtained with the described organo-mineral process appears very precise. Also, the outputs are shown in figure 8-b, showing the “bell-curve” distribution of the outputs, in agreement with the theory [16]. Its main use is related to the PHASAR, an important component for communication.

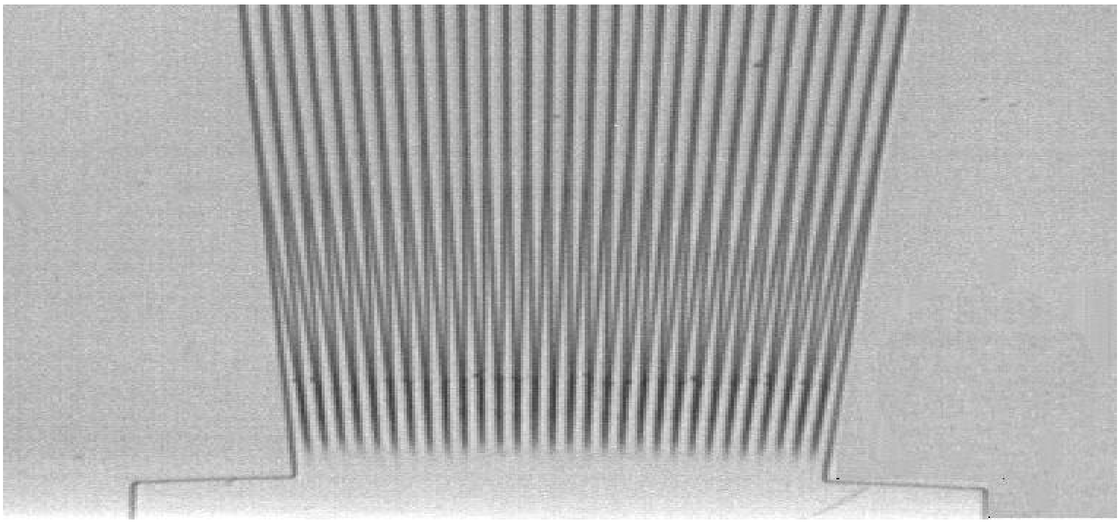

Figure 8-a : Top view of a star coupler device made with the organic-inorganic material.

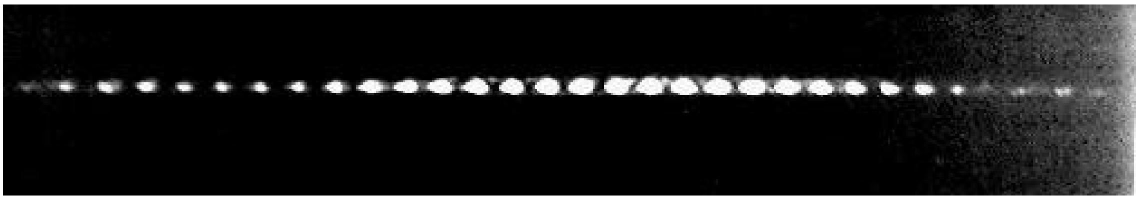

Figure 8-b : Outputs of a star coupler device made with the organic-inorganic material.

A more complex device is also demonstrated with circuits using the multimode interference effect (MMI). The principle is based on interference of guided modes which lead to light patterns reconstructed after a definite length in a strongly multimode structure. An incident electromagnetic field E(x,y,z) is injected from a single mode guide into a large multimode structure. Each excited mode in the large guide has a specific propagation constant, i.e. a propagation speed. After definite propagation distances, in the multimode guide, the total field profile, which corresponds to the superposition of the fields associated with each guided mode, shows multiple peaks in the lateral dimension which can be exploited.

The detailed analysis can be seen in ref [17] : Considering each field related to mode k written $E_k(x,y)$. $\exp(-j\beta_k z)$, one can see that for a certain distance for z=2L, the global profile is reconstructed as an image of the input if $\exp(-j\beta_k z) = 1$ i.e. if the number of "real" wavelengths ($\lambda_k = \lambda_o / n_{eff,k}$) is an integer for each mode k, or else if the phase change is a multiple of 2π. Besides this particular distance z= 2 L, it is remarkable that at distances L/n, the global profile presents n peaks laterally, explained by combination of modes with various but equally distributed phase changes. The evolution of the profile field in such a device can be experimented by simulation on the Internet [18].

The MMI device can be designed to offer homogeneous light peaks injecting equal part of the input light into output waveguides, it acts as a power divider for a specific range of wavelengths, with a low value of loss. The interest of such a device is the possibility to make very short n x m power splitter, thus increasing the possibilities of integration, in order to make PHASAR or Dense Wavelength Division Multiplexer (DWDM) for instance.

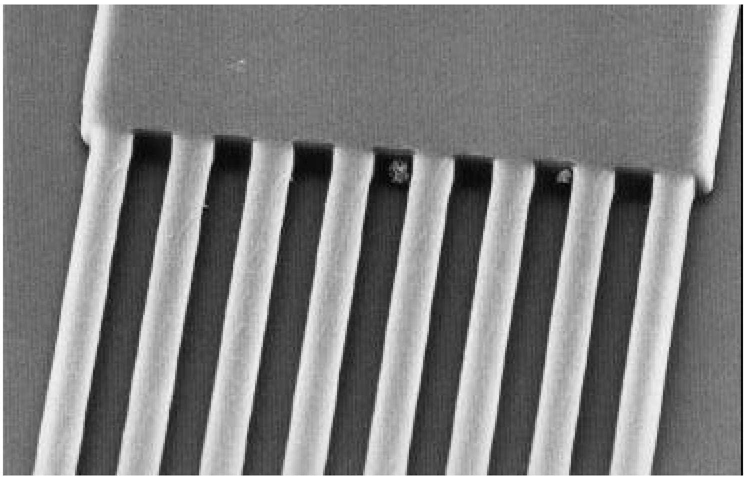

Figure 9 : Top view of the outputs of a MMI component.

Using the MMI effect, 1 x 8, 1 x 16 and 1 x 32 power splitter for use at 1.55µm wavelength are made on the organic-inorganic material structure. Figure 9 shows a top view of the MMI guide and starting output guides made according to ridge structure. A photograph (figure 10) shows the outputs of the 1 x 32 circuit excited at 1.55µm. The division is obtained after a distance in the multimode guide inferior to 6 mm. The total length of the device can be as low as 1.5 cm, including the output S-bends to make physical separation of the waveguides (200 µm) in order to connect optical fibers.

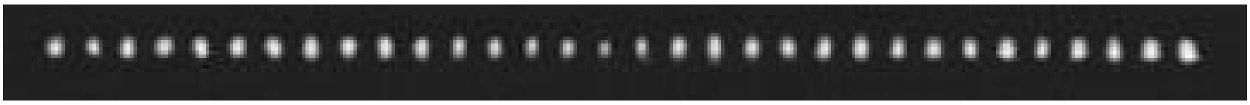

Figure 10 : Outputs of a 1 x 32 MMI splitter.

This should be a good alternative to the star-couplers conventionally used in integrated optics devices such as DWDM. Phasar with star-couplers have otherwise been made in this technology and should be soon put on the market by LUMENON, Canada.

Perspectives

The flexibility of the technology and its variants allow the fabrication of low cost optical components. Many components can be imagined by simply designing masks, or driving a laser writing according to any configuration. The selection of values for the index change introduces even more possibilities.

To be definitively credible, the organo-mineral circuits have to be compatible with optical fiber interconnects. Recent studies shows that active connection can be achieved between optical fiber and organo mineral waveguides. This solution however is relatively expensive. A process, which should allow a passive connection with optical fiber, is presently in progress [19]. Figure 11 shows a waveguide and the buffer layer limited to the center of the substrate, which can be aligned with a V-groove in this process.

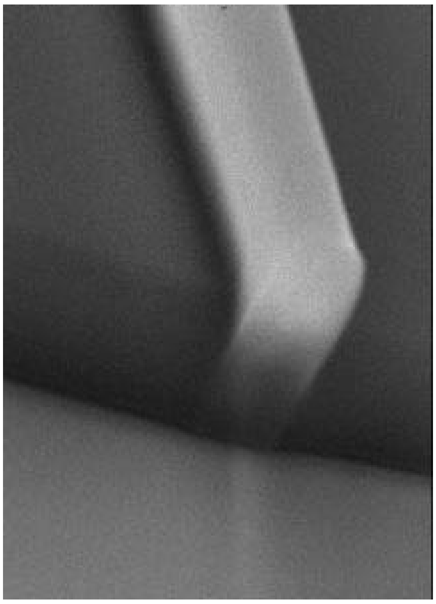

Figure 11 : Stopped ridge waveguide (SEM photograph).

Variants in the technology include the doping of the material with rare earth components. Mineral sol-gel material amplifiers have been demonstrated [20]. Now the reduction on the OH absorption is studied in the organo-mineral counterpart : luminescence have been observed [21].

Conclusion

Organo-mineral material is a new alternative for integrated optical circuit fabrication. High quality channel waveguides are made using low cost equipment. The physical, optical parameters, geometrical strcutures can vary according to the envisaged application. Conventional passive circuits can be fabricated, and active circuits (amplifiers) can be predicted. The compatibility of the organic-inorganic technology and the routing device shown here, opens the way to a low cost fabrication of complex dense devices such as WDMs in optical communication systems.

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