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Photonic circuits writing with UV pulsed laser

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Photonics technology is employed in a growing number of applications. Biological and chemical sensors (E. Udd, Fiber Optic Sensors: An Introduction for Engineers and Scientists, Wiley, New York, 1991 [1]) for health and environment demand an adaptable technology. Network development towards the end-user requires more interconnecting components. Vision, lighting, data processing in hostile environment (spatial, military) need specific technologies. A flexible and low-cost process using good quality material is necessary. The sol-gel process is a chemical method to fabricate glasses at ambient pressure and moderate temperature. Hybrid materials (H.K. Schmidt et al., Proc. SPIE **3136**, 220 (1997) [2]), mixing organic and inorganic parts, offer the advantages of polymer-like materials and glasses. We report on a new hybrid sol-gel technology to overcome the drawbacks of the formerly presented one (H. Krug, F. Teillantes, P.W. Oliviers, and H. Schmidt, Proc. SPIE **1758**, 448 (1992) [3]). We present the material synthesis, an accurate and flexible fabrication process based on a pulsed UV laser lithography system and the characterisation of the optical waveguides and photonic circuits realised.

1 Introduction During the last ten years, the fabrication of 3D waveguides and more recently integrated optical circuits (COI) using organic-inorganic hybrid precursors has received an increasing amount of attention [4, 5]. ORganically MOdified SILicates [$R_xSi(OR)_{4-x}$] prepared by sol-gel process were particularly attractive for integrated optics fabrication. A composition based on MAPTMS has already allowed the industrial fabrication of optical integrated devices. For this kind of materials, the polymerization of the organic network is typical of free radical kind.

In this work, we fabricate waveguides from another hybrid precursor, the EETMOS mixed with a cationic photoinitiator. We explain the sol-gel synthesis of the material optimized so as to lower absorption due to mineral network. Then the fabrication process is detailed: thin films, deposited by dip-coating on silicon substrates, are processed using a pulsed UV laser writing system. Laser writing permits to precisely localise the UV irradiation that initiates the organic network polymerization. Finally, the characterisation of the first waveguides and circuits performances are presented. This new technique should be compatible with good performances, low-cost process and mass production.

2 Material synthesis The simplest and lowest cost way is based on a peculiar precursor of the general formula $R'Si(OR)_3$ which has two reactive parts in such a way that it offers a two step polymerisa-

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tion process. A mineral network can be fabricated by polycondensation of the sol-gel part of the precursor (-Si(OR)$_3$) (Fig. 1) and an organic network can be created too by UV photopolymerisation of a carbon double bond group of the precursor (R'-). The more advanced and industrialised material is based on a mixture of methacryloxypropyltrimethoxysilane (MAPTMS) and zirconate propoxide chelated by methacrylic acid [3].

To overcome its drawbacks (low mechanical properties, poor adherence on silicon and even on glass, propagation losses too high at 1.55 µm wavelength, important internal stresses after UV curing, inhibition of polymerization process by oxygen) we explore the way of a new generation of organic-inorganic materials whose organic part is photopolymerized using cationic way which is known to be insensitive to oxygen and thus permits optimisation of the network properties. After literature study we choose the 2-(3,4 epoxycyclohexylethyltrimethoxysilane) (EETMOS) (Fig. 1) because of its very important reactivity and its high conversion rate [6], as well as low shrinkage and good adherence. It is well known that Si-OH groups compete with propagation of the light by absorption process at 1310 nm and 1550 nm (second and third telecommunication windows). These groups are known to be present in hybrid materials because of the low temperature treatment necessary to preserve the organic part. To minimize them, a peculiar attention has to be made in the sol synthesis which must contain after hydrolysis of the sol-gel part the lowest Si-OH amount. Hydrolysis and condensation rates were studied using Nuclear Magnetic Resonance around Si atoms (Si-NMR) for different solutions.

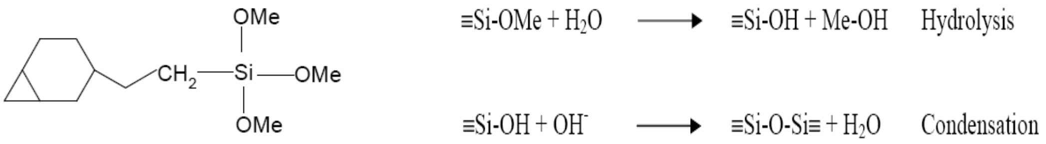

Fig. 1 EETMOS structure and sol-gel process.

Our study is done using four synthesis conditions. Sol labelled A corresponds to EETMOS hydrolysis rate of 3 with HCl 0.1N. However, as EETMOS and water are not miscible, an addition 0.8 mole of ethyl alcohol (99%) (for 1 mole EETMOS) is necessary. The solution is kept stirring for 8 days. In the sol labelled B, HCl is replaced by water to hydrolyse in neutral conditions. The solution is kept stirring for 6 days. The sol C corresponds to a hydrolysis rate of 10 with HCl 0.1N. The solution is stirred for 6 days at room temperature. Sol labelled D corresponds to the sol C with the drop wise addition of a HF/Ethanol (0.7 mole of ethanol for 1 mole EETMOS) solution at the end of the synthesis. The solution is kept for stirring two more days at room temperature. It appeared, through NMR studies, that solution D gives the lower amount of Si-OH bonds. Using HF like a base in a double step process increases the condensation reactions, to leave in the solution only few silanol groups on oligomers species. This solution is the one under study to realise integrated optical circuits.

3 Fabrication process To build a 3D waveguide on the silicon substrate, the equivalent of an optical fibre structure has to be fabricated: a high index core is surrounded by a lower index cladding. Four steps are then necessary. First, a buffer layer is deposited on silicon. It must have both a thickness high enough to isolate the future 3D guide from the high refractive index of silicon, and must have a refractive index lower then the future 3D waveguide core. Then a second layer is deposited using the peculiar precursor cited above. It is then locally cured under UV irradiation. The unpolymerized part is then dissolved in classical alcohols which reveal 3D guides. Finally, a thermal treatment around 100 °C allows the polycondensation of sol gel part and gives to the guide good mechanical properties and very long time stability. In the last step, the relief guide is covered by the same layer used as buffer to protect against external aggressions. The layers are deposited using dip-coating method under ambient atmosphere. The thickness is 5 µm for each layer. Wave guide core dimensions are design to work under single mode behaviour at 1310 nm, which is the second telecommunication window and for which the absorption losses are less sensitive to remaining Si-OH group than at 1550 nm. So as to minimise coupling losses with optical fibres, the transverse wave guiding structure is defined to be 5x5 µm^2 with an index difference between core and cladding of 0.01. Buffer layer index was adapted to match those criterions.

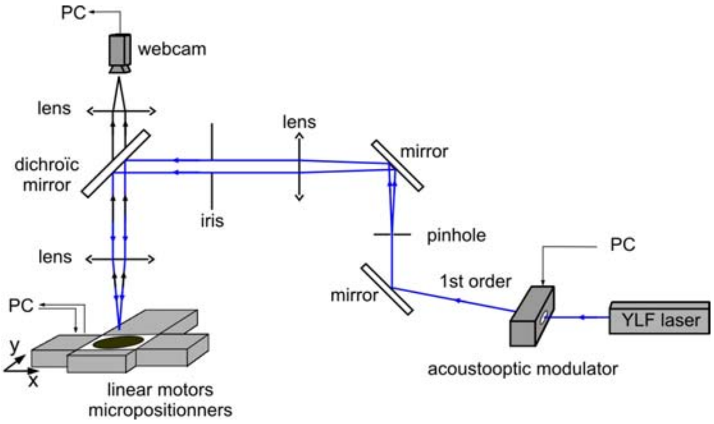

Fig. 2 Laser writing system.

The photolithography step is performed using a pulsed laser writing system (Fig. 2) instead of a lamp and mask system, which gives poor patterning resolution on thick layers (several micrometers) due to diffraction on the mask edges. The system is based on the imaging of a finite distance object defined by the illumination of a pinhole. The diffraction pattern propagating for the object is collimated, filtered and focused to build the image of the object so as to ensure, vertical energy walls during irradiation and circular symmetry. An acousto-optic modulator is placed on the laser beam path; diffracted orders are selected using the pinhole and thus, power control and fast switching of the writing laser spot can be performed. During layer irradiation some photons are diffused and photoluminescence occurring in the blue can be observed. Capturing this image through a dichroïc mirror with a camera permits us to monitor spot geometry and power. The laser source is a diode pumped Nd:YLF, which is frequency quadrupled to emit at 262 nm wavelength; its repetition rate is adjustable between 3 to 60 kHz, and pulse duration is 10 ns for an average power of 12 mW. The layer to be exposed is dynamically irradiated by being translated under the fixed laser spot. The displacement is realised with high accuracy linear motors based micropositionners driven by a computer. Drawn designs are thus easy to modify; this gives flexibility to the patterning process and enables the realisation of different prototypes circuits. Waveguides were written using an energy density of 6 J/cm^2.

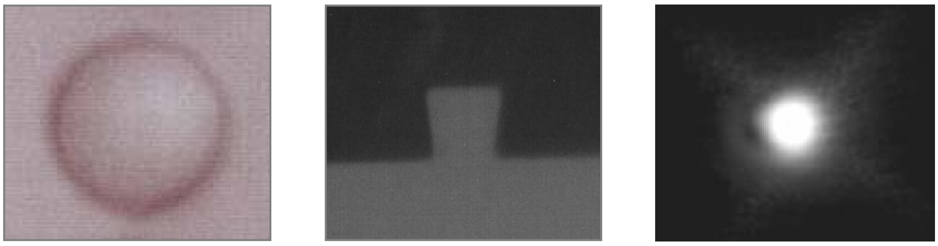

Fig. 3 1st and 2nd: Optical microscopy photography of a pulse impact (top view) and linear waveguide (cross section) respectively; 3rd: fundamental mode waveguide output near field image at $\lambda = 1310$ nm.

4 Characterisation Straight waveguides designed to be single mode at 1310 nm wavelength were first fabricated. As it can be seen in Fig. 3, one laser pulse impacts and straight waveguide's section are accurately defined, sidewalls are straight and corners well defined due to the well confined laser irradiation.

The index difference could be set so as to obtain single mode waveguides (Fig. 3). Coupling and propagation losses were measured using the cut-back method. Coupling losses are close to theoretical ones due to mode mismatch between waveguide and fibre, which core diameter is 9 µm. Propagation losses are 1.85 dB/cm. Bending losses in curved waveguides were measured as a function of curvature radius. Fitting between experimental data and theory could ensure us with in situ evaluation of index difference leading to a 0.01 value. Y junction power divider and directional couplers were fabricated, and the good quality of etching in branching region (Fig. 4) is promising in terms of devices performance. A 3dB coupler with 0.01 dB non uniformity illustrates the branching quality of Y junction power dividers (Fig. 3).

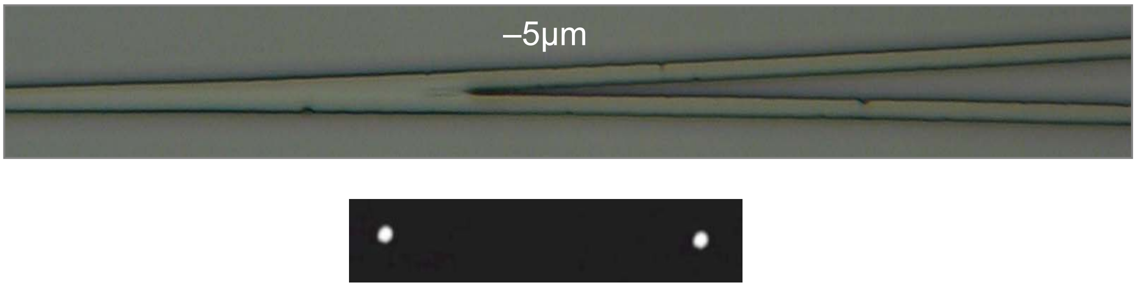

Fig. 4 Top: top view of a Y junction power divider; bottom: Y junction output images at $\lambda = 1310$ nm.

5 Conclusion A new flexible and low cost technology for integrated optical circuits fabrication has been developed based on hybrid materials polymerized through sol-gel process and pulsed UV laser writing system. Cycloaliphatic epoxyde type EETMOS material has been chosen and its mineral network properties have been optimised in regards with Si-OH absorption in second and third telecommunication windows. A fabrication process permitting flexible and accurate patterning of the wave guiding layer is operational and first devices have been fabricated. Propagation losses are still under study through optimisation of the material synthesis, especially the organic network, and of the fabrication process and the laser lithography system.

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