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SPACE GATOR, A GIANT LEAP FOR FIBER OPTIC SENSING

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Abstract - **Fibre Optic Sensing is a rapidly growing application field for Photonics Integrated Circuits (PIC) technology. PIC technology is regarded enabling for required performances and miniaturization of next generation fibre optic sensing instrumentation. So far a number of Application Specific Photonics Integrated Circuits (ASPIC) based interrogator systems have been realized as operational system-on-chip devices. These circuits have shown that all basic building blocks are working and complete interrogator on chip solutions can be produced. Within the Saristu (FP7) project several high reliability solutions for fibre optic sensing in Aeronautics are being developed, combining the specifically required performance aspects for the different sensing applications: damage detection, impact detection, load monitoring and shape sensing (including redundancy aspects and time division features). Further developments based on devices and taking into account specific space requirements (like radiation aspects) will lead to the Space Gator, which is a radiation tolerant highly integrated Fibre Bragg Grating (FBG) interrogator on chip. Once developed and qualified the Space Gator will be a giant leap for fibre optic sensing in future space applications.**

I. INTRODUCTION

Fibre Bragg Grating (FBG) sensors have been around for several decades and even applied for harsh environments in a wide range of market segments. Recent advances in Integrated Photonics however have led to readout systems which exhibit unprecedented performance in several fields. The readout units are extremely low mass, vacuum compatible, rigid and exhibit a high reliability. They can be configured to readout several sensors at the same time. Fast multiplexing will allow to readout hundreds of sensors with a single system and sensitivities down to nano-strain have already been demonstrated using interferometer on chip implementations. At this moment in time these technologies are being designed into multiple applications for demanding terrestrial market segments but it is felt that similar performance can be benificial for several space applications as well.

In this paper a number of FBG interrogator systems build on so called Application Specific Photonic Integrated Circuits (ASPIC) are presented. They were manufactured as system-on-chip modules, capable of providing impressing performance versatility with regard to aspects as resolution, speed, low costs and multiplexing capabilities. Also addressed in this paper is the significance of well-designed generic and custom packaging of optical chips is being addressed. As Integrated Photonics is becoming a more and more mature industry, foundries for chip manufacturing are being setup, design houses are founded and the development of the first commercial applications has started.

But a bare chip will not work in any application. An important step in the supply chain arises with the need to link up optical chips to the rest of the world. For many components and sub-systems the way they are packaged is directly llinked to system reliability and costs. It is the combination of good ASPIC designs as well as dedicated and optimized packaging that will prove this next generation technology worthy for serving applications in demanding markets like space. Although performances in its relevant versatility does not seems to be an issue anymore, and although the technology appears highly reliable, many questions for instance with regard to radiation and extreme temperature endurance are still being answered at this moment. Fortunately, considerable work has been done already in this area and will be done in the near future for various terrestrial applications. Both optical fibres and integrated photonics it's early stages have been subject to testing and evaluation for harsh environment and major steps have been taken in the development of fiber optic connectors for space applications. The availability of ASPIC based FBG interrogator systems like the Gator, its demonstrated performances and the growing need for smaller and cheaper devices with less footprint is, paving the way to reliable and space worthy fibre optic sensing systems.

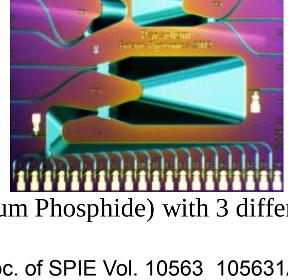

Fig 1. ASPIC (Indium Phosphide) with 3 different AWG functions

II. INTEGRATED PHOTONICS

An ASPIC is an optical chip designed for a dedicated purpose. Similar to micro-electronics, Aspic's allow a variety of solutions, all based on a small set of basic building blocks that are capable of transporting and modulating base properties of light, i.e. phase, amplitude and polarization.

Unlike integrated electronics where silicon is the dominant material, Aspic's have been fabricated on different material platforms, each of them providing advantages and limitations depending on the functions to be integrated. For instance, Silica has desirable properties for passive components like Arrayed Waveguide Gratings (AWG) while Gallium Arsenide (GaAs) or Indium Phosphide (InP) allow direct integration of active components, i.e. light sources, detectors, etc. Although the fabrication process is similar to integrated electronics, there is no dominant device like the transistor.

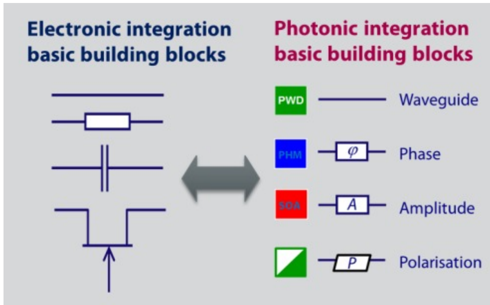

Fig 2. Basic building blocks

The range of photonic functions including low loss interconnected waveguides, power splitters, optical amplifiers, optical modulators, filters, lasers, detectors, etc. The versatile ability to replace traditional assemblies of multiple discrete optical or micro-optical components by a single small sized chip makes ASPIC technology favorable for next generation optical systems for benefits in cost reduction, functionality aggregation and standardization of specifications and processes. Certainly this broad applicable versatility requires the need for standardization to preserve compatibility between the development platforms, allowing integration the best of worlds to provide the best possible solution available. In that respect valuable lessons in platform material selection for ASPIC are repeatedly discussed. This will ultimately contribute significantly to the success of the ASPIC technology. As cost and performance may currently prove silicon-based devices preferable, it is certainly the capability of having both passive and active functions combined that proves InP more worthwhile in some cases depending on the required system functionality. And although originally the technology has been mostly driven by the data- and telecommunication market other applications like sensing demonstrate a increase in interest because of this versatility.

III. FIBRE OPTIC SENSING

As said, data- and telecommunication needs have been the major driver for integrated photonics, other applications fields appear to gain increasing necessity for smaller sized, more affordable and repeatable and reliable performance devices just as well. Fibre optic sensing is a rapidly growing application field for ASPIC technology. The sensing principle that is primarily being addressed in this paper regards the use of the Fibre Bragg Grating, which is basically a longitudinal periodic variation in the refractive index of the core of the fibre exposing a stress and thermal-optic effect which makes them useful for sensing.

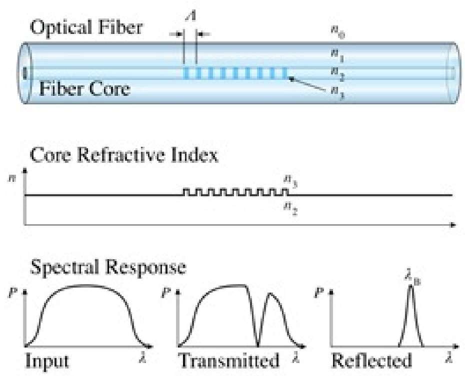

Fig 3. Fibre Bragg Grating sensing principle

Thermal and mechanical stresses cause strain variations in the fibre; the variations cause a varying period and with that a variation in the reflected wavelength. The measured wavelength varies linearly with temperature and/or strain by:

$$\frac{\Delta\lambda_B}{\lambda_B} = C_S\epsilon + C_T\Delta T \tag{1}$$

In which λ_B is the peak wavelength, $\Delta\lambda_B$ the change in peak wavelength, C_S is the strain coefficient, C_T the temperature coefficient, ΔT the change in temperature and ε the strain. Each FBG in the optical fibre with its own period and thereby a unique reflection wavelength, can be identified as a single measuring point distinguished in the detection process. As the spectrometry approach provides sufficient performances for many applications, an additional method for achieving an even higher resolution of wavelength shift detection is based on adding interferometry functionality. To prove the system concept a fibre optic based Mach-Zehnder interferometer was build (called MAZE) to access the measurement concept (see image below). This setup clearly demonstrated the non-practibility of having such fibre optic based systems for extreme high resolution strain measurements. Its size, weight and moreover its susceptibility to environmental influences made it unacceptable for operational measurements in extreme demanding environments.

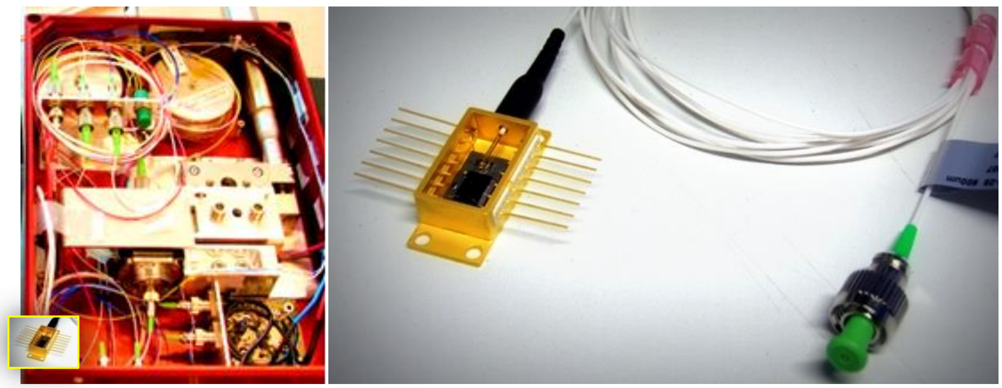

Fig 4. The left image shows a fiber optic based Mach Zehnder Interferometer used for high resolution FBG interrogation. The right image shows its ASPIC equivalent, demonstrating similar specifications but with smaller dimensions, improved stability, etc.

With the introduction of ASPIC technology a significant number of performance issues, if not all, can be optimized drastically. As a comparison, the same optical system was build using ASPIC technology. The image below shows the equivalent ASPIC system. This prototype immediately demonstrated significant advantages: solid state, small size, lower mass, less power, less costs, and by that an improved controllability, thermal and vibration stability. Perhaps even more important than the above an improved reliability and repeatability.

IV. GATOR

Since then, a number of ASPIC based FBG interrogator systems are being realized as operational system-on-chip devices, each of them with a specific performance definition, dedicated for a specific application and designed towards a key performance; measurement resolution, sample speed, manufacturing costs and multiplexing capability, or a combination of those:

Table 1. Gator based FBG interrogator systems

System	Specifications	Application(s)
Gator	1 pm, 20 kHz	Basic ASPIC system, all purpose
Casgator	100 fm, 20 kHz	Damage detection in composite structures
Ladygator	10 fm, 40 kHz	General purpose high resolution system
Ladybug	1 fm, 80 kHz	Vibration control, temperature mapping
Supergator	100 fm, 20 Mhz	Acoustic-optical imaging
Grasshopper	3 pm, 1 kHz	Low cost, OEM module
Ant	1x8 optical switch	Multiplexing capability, general purpose

The interrogation principle of the Gator series and affiliated systems like Ladybug, Grasshopper and Ant is based on spectrometry and an added interferometry function for higher resolution. The Gator chip design consists of a modified Arrayed Waveguide Grating (AWG) (patented technology) and a photodiode at the output of each AWG channel. For telecom applications the aim is to minimize the crosstalk between different AWG channels as much as possible. For the Gator application crosstalk is actually a desired effect. The Gator AWG is modified such that the crosstalk between adjacent channels increases. An example of AWG transmission spectra for a modified AWG is shown in the next figure. The AWG channel response is plotted in red, the FBG reflection spectra are plotted in blue.

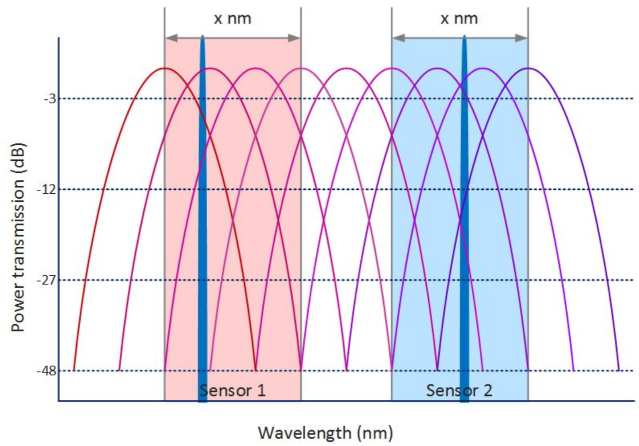

Fig 5. Modified AWG with crosstalk

This AWG modification makes it possible to performing high resolution wavelength shift detections over the full range of the AWG. By changing the Free Propagating Region (FPR) of the AWG the effect of crosstalk is made worse on purpose.

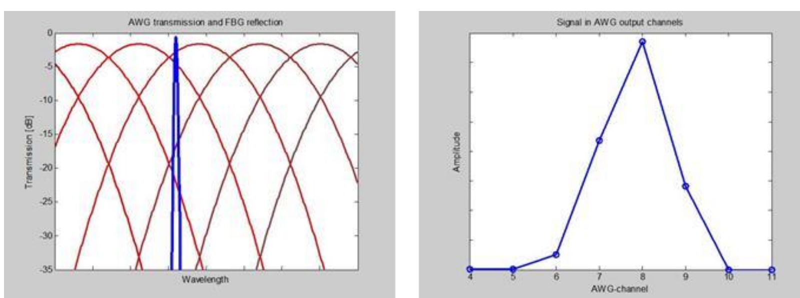

Fig 6. The left image illustrates the AWG channels in red and the FBG reflection spectrum in blue. The right image shows the amplitude of the signal in multiple AWG channels

The reflected wavelength spectrum from the FBG overlaps with multiple AWG channels. This means light is coupled into multiple AWG channels. By placing a photodiode at each AWG output channel, the power distribution can be monitored. An algorithm is used to determine the wavelength shift of each FBG. This algorithm calculates the central wavelength of the FBG and is linearly related to a strain value.

An example of a packaged Gator interrogator on chip is shown in the picture below. This prototype Gator chip has 36 photodiodes bonded to a ROIC (Xenics). A standard Gator has about 55 of these photodiodes. The ROIC component can handle up to 512 or even 1024 inputs, leaving sufficient room for expansion if necessary.

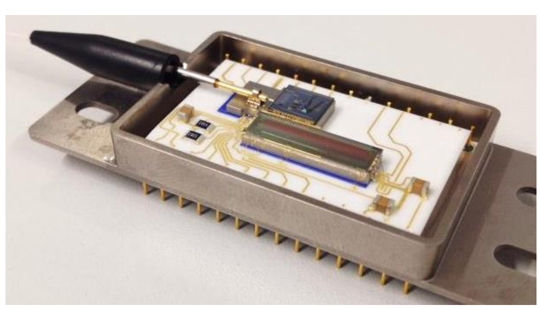

Fig 7. Packaged prototype Gator chip

V. SPACEGATOR

One of the application areas in which ASPIC technology can prove its versatility and reliability is Aeronautics and Space. The versatility of ASPIC technology allows combining the specifically required performance aspects for the different sensing applications: damage detection, impact detection, load monitoring and shape sensing, including redundancy aspects and time division features for channel multiplexing.

The Spacegator is considered a space qualified version of any of the ASPIC base Gator systems mentioned in the table. Ongoing developments based on strict requirements will eventually lead to application qualified systems providing multi-performance sensing and processing capability. Once developed and qualified, this new State of the Art fibre optic sensing equipment will be a gigantic step forwards in future sensing applications on all levels. Considering extreme requirements with regard to dedicated versatility in functionality, reliability and environmental endurance the following technical issues are being addressed generally:

- Radiation and high temperature harnessing;
- System redundancy by bi-directional interrogation;
- Channel multiplexing by time division multiplexing;
- Inclusion of high-speed data communication capability;
- Smart sensor network concepts for data transfer bandwidth optimization;
- Technology Readiness Level assessments.

One of the major reliability issues that is of current interest and needs to be investigated more extensively is radiation hardiness. Fibre optics has been subject to numerous tests developments already which led to the commercial availability of radiation hardened fibers. For instance the DrakaElite™ fibers have been improved for use in radiative environments (e.g. gamma rays, X-flash, neutrons, protons) allowing them to be used for data transmission in environments of military, defense, aeronautics, space, nuclear power plants, high energy physics laboratories, and sensors in general. Little investigation is been done yet on this matter for integrated photonics. There have been performed few experiments on InP for optical transceiver modules for space [1] and radiation tests on Mach Zehnder modulators for high energy physics environments [2] for which the results unfortunately where inconclusive yet. But although the InP transceiver experiments show promising results more investigation is needed, and perhaps more specifically regarding the hybrid integration of ASPIC technology with (opto)-electronics.

VI. RELIABILITY & PACKAGING

In all its benefits and possibilities ASPIC technology appears enabling for the development of small, stable and reliable systems for fibre optic sensing devices serving a wide range of applications and markets. So far, several operational prototypes have been fabricated for different performances for specific measurement applications proving the capability and versatility. Prototypes that are already operational have resolutions ranging from 1 micro-strain to 0,1 nano-strain, and sampling speeds of 1 kHz up to 7 MHz. But more important for demanding applications is that the technology proves reliable. Hence, integrators and solution providers are concerned with questions like:

- What is the environmental tolerance of the technology?
- What is the qualification status and what does the roadmap to full qualification status look like?
- How reliable are the solutions?

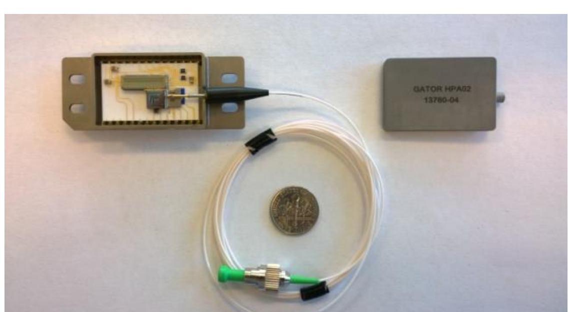

Fig 8. Packaged Gator FBG interrogator system

Not only the performance reliability is an important issue, also on-time delivery and even more significantly, reliable packaging of ASPIC's. Achieving a high degree of assurance requires consolidation of the supply chain that is focused on delivery of state of the art technology and not on academic progress. To answer the questions and to come to a fully applicable delivery, the complete chain should include all steps from academic developments to fully packed solutions. Only this allows fast, efficient and qualified ASPIC's for demanding applications. Observing a growing maturity of Integrated Photonics, foundry services have been set up, several design houses have been founded and development of the first commercial applications has started. But a bare photonic chip will not work in an application. An important missing step in the supply chain becomes clear as soon as you need to link your chip with the rest of the world. The required packaging service is not offered by the IC-packaging companies. Wire bonding is no problem but it starts to be difficult as soon as attaching fiber (arrays) to the chip is required.

For many components and sub-systems the way they are packaged is imperative with regard to system reliability and costs. Projects where reliability is key (like space projects) tend to opt for fully hermetic packages. Although this generally leads to very high system reliability, it also tends to drastically increase costs. Consequently commercial applications tend to opt for other types of packaging which in turn can lead to reliability issues when the package is not designed to meet the required quality criteria and the packaging is not properly performed. Photonic integrated circuits tend to pose severe requirements with respect to cleanliness and alignment next to the more common environmental sealing, which will have to be satisfied all to lead to an acceptable solution. The complexity of photonic subsystems and components vary from simple detectors to complex optical systems containing several sensitive components. Almost without exception, a number of strict requirements are posed to photonic systems:

- The components need precise alignment relative to each other and external mechanical references
- Several electrical connections will have to be made
- During assembly contamination of the optical components shall be avoided
- The system will have to exhibit a high reliability and function flawlessly over a prolonged period in time
- Most miniaturized packaging requires a dedicated design for temperature stabilization

Which requirement is most stringent generally depends on the application and exact composition of the components to be packaged but in many cases the costs and efforts associated with proper packaging are largely underestimated. In addition packaging is usually forgotten till the ASPIC has been made, with a non-optimal working device, or even impossible to package device as result. Integrated photonic circuits generally need to be aligned with one or more optical fibres at micro-meter precision, next to this it is common to have thermal stability requirements in the milli-Kelvin range to obtain the required wavelength stability of the optical circuits.

As cleaning afterwards is seldom an option, due care shall be given to packaging and alignment issues well in advance of the actual packaging process to avoid contamination and misalignment issues. For high frequency applications above 1 GHz the match between package (case, wire bonds, PCB boards, etc.) and ASPIC is of at most importance. As customer acceptance is often associated with the pricing of the system and reliability issues are often related to financial risks it is important to work towards solutions which are both highly reliable and affordable. This can only be obtained if the reliability of the package and packaging methods used is taken into account from the early design stages. It is for this reason that it can be expected that now real life applications of integrated photonic circuits are becoming more common, the importance of reliably and cost effective packaging will increase.

VII. CONCLUSION

With the availability of ASPIC technology many doors are opened towards sensing solutions for harsh and demanding environments. Where characteristics like size, weight, costs etc. play major roles, systems based on this next generation technology can provide the means required. And although significant non-recurring costs are involved in the design of an ASPIC and the initial system, the high reproducibility and stability of the chips not only ensure a high level of repeatability but also significantly lower recurring costs than those associated with the reproduction of free space optics based systems.

The development for Gator based systems for Space and Aeronautics continues progressively and is expected to provide significant advantages in metrology systems for satellites. Reliability and long-life operation capability are important factors that are being addressed in the next years; multiple endurance tests for various radiation types and temperature are planned, both for terrestrial and space application purposes. Together with the work that has been done so far the future of integrated photonics in space looks extremely promising.

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