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1- Context

1.1- Introduction

Photonics systems, sub-systems and components are found in an increasing number of applications of many high technology industry segments. This remark applies particularly to space-embarked systems, which rely on the versatility and reliability of photonic systems to realize many of the critical functions needed to insure their safe and durable operation.

Many embarked space photonic systems use light modulators as a key component to achieve intensity or phase modulation of various light sources at different operating wavelengths: In particular, the electro-optic Lithium Niobate ($LiNbO_3$) modulators offer a unique combination of performance that makes them prime candidates, not only to satisfy the optical system specifications, but also to meet the tough requirements of space operation.

1.2- $LiNbO_3$ Modulators and other electro-optic modulators

The $LiNbO_3$ based modulator is one of the many optical modulators that have been developed in recent years. Other materials (e.g., InP, GaAs) based modulators have been also used to make external light modulators. Initially, the development of these modulators was driven by the fiber optic telecommunication market that needed ever increasing modulation speeds. Today, E-O modulators are used in a large number of both telecom and non-telecom applications. The benefits and drawbacks of the main optical commercially available modulators are contrasted in the table below: It is clear that the $LiNbO_3$ E-O modulator offers the most attractive combination of performance, versatility and cost.

For space applications, the accumulated number of hours of operation and the proven reliability of $LiNbO_3$ modulators make them a very attractive choice compared with products issued from competing technologies.

In addition, the $LiNbO_3$ modulators, beside their long standing proven record of use in many applications, and their many comprehensive successful qualifications (e.g., Telcordia) offer both a large optical bandwidth, ranging from 780 nm to 2500 nm, and a very broad electro-optic modulation bandwidth (> 40 GHz).

Thanks to their unique combination of performance, $LiNbO_3$ modulators are used in very diverse space applications that include navigation, measure–countermeasure, telecommunications, sensing, etc…

Benefits	Drawbacks
Polymer Modulators (polymer on silicon)	
• potentially low cost	• aging of the polymer is a question mark as far the long term reliability of the device is concerned • only telecom λ (1550nm) as of today • only one commercial vendor • no significant performance benefits
Semiconductor modulators (GaAs & InP)	
• several established vendors • small footprints for InP • expected good reliability	• restricted to 1310 nm / 1550 nm • high insertion loss as standalone modulator • some chirp issues • limitations of bandwidth with InP
Silicon Photonic modulators	
• very small footprint	• not a mature technology • only one vendor • restricted to datacom • very high insertion losses
LiNbO3 modulators	
• mature technology (x100 thousands of operating devices since the mid- 90's) • proven reliability • already in space • several well established vendors • Choice of commercially available wavelengths	• larger footprint

Table1: Comparison of E-O light modulator technologies

2- Applications of $LiNbO_3$ modulators in space

2.1 Fiber optic gyroscopes

Fiber optics gyroscopes (FOGs) are high performance sensors used in demanding navigation systems. It is now proven that they can overtake the performance of classical laser gyroscopes, with the benefit of a smaller footprint, lower weight and lower cost. Systems with accuracy better than 0.001°C/hour are commercially available, and FOGs based navigation systems have been used in satellites since 2010. These FOG modules integrate custom designed $LiNbO_3$ phase modulators.

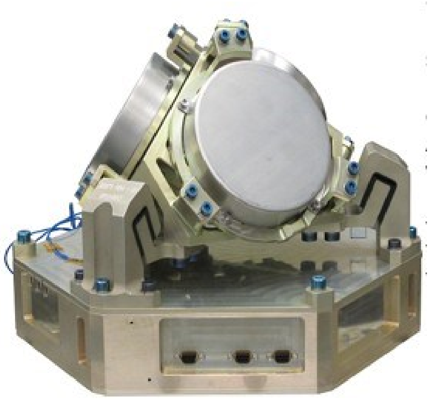

Figure 1: A three axis ASTRIX Fibre Optic Inertial Measurement Unit from AIRBUS DEFENCE & SPACE (formerly ASTRIUM). This unit is designed for long lifetime mission. Each axis uses a $LiNbO_3$ modulator. All opto-electronics and opto components are fully compliant to HiRel Telecom satellite standard (SCC-B or equivalent).

2.1 Inter-satellite communications

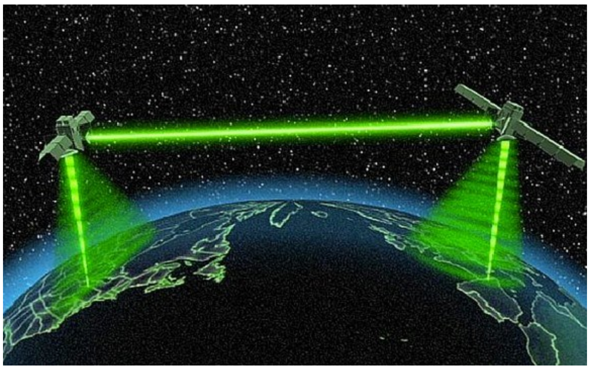

Figure2: Artist's view of FSO (Free Space Optics) communication demonstrations

Free-space optical communication has been implemented between satellites since the 90's using directly modulated high power laser diodes at 820-850 nm. The emergence of fiber lasers in the near infrared and the availability of $LiNbO_3$ modulators in this band have made possible space optical links using more efficient modulation formats and offering improved data rates and BER.

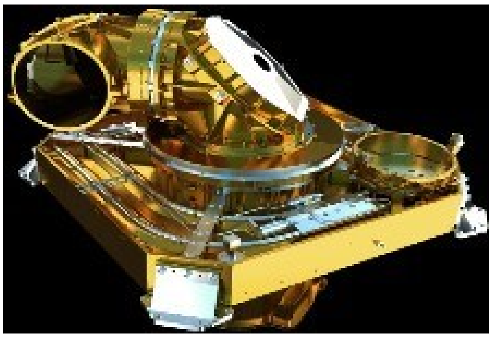

Figure3: A Laser Communication Terminal (LCT) from the German space equipment supplier TESAT-SPACECOM. This LCT implement external phase shift keying modulation together with coherent detection.

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2.3 Optical instruments for scientific missions

Light can be used to measure many physical quantities, therefore one can see many scientific satellites with optical instruments on board. Some incorporate external modulators; GRACE-FO mission whose task is to map the Earth gravity is an example.

The Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) mission is a partnership between NASA and the German Research Centre for Geosciences (GFZ). GRACE-FO is a successor to the original GRACE1 mission and is designed to dramatically improve the already remarkable precision of its measurement system.

The GRACE missions measure variations in gravity over Earth's surface, producing a new map of the gravity field every 30 days. Thus, GRACE1 shows how the planet's gravity differs not only from one location to another, but also from one period of time to another.

For GRACE1, the method to map gravitational fields consists of two nearly identical satellites. One follows the other along the same orbit as both continually measure the distance between them by means of microwave ranging instruments.

The two GRACE-FO satellites will use the same kind of microwave ranging system as GRACE1, and so can expect to achieve a similar level of precision. But they will also test an experimental instrument using lasers instead of microwaves, which promises to make the measurement of their separation distance **at least 20 times more accurate**. Phase modulators are used to stabilize the laser cavities of the optical range finding system. The two satellites should to be launched in 2017.

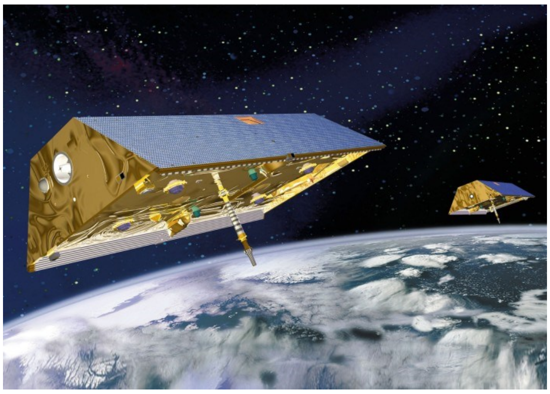

Figure 4: Like GRACE1, the follow-on mission will consist of two spacecrafts orbiting Earth in tandem

2.4 Microwave photonic payload sub-systems (project)

Over the past few years, innovative payload concepts based on photonic technologies have been investigated by the manufacturers of communications satellites. Several architectures were elaborated covering different application cases including flexible analogue repeaters based on a photonic center section, and photonic receiver front-ends for advanced antennas allowing digital beam forming. Such architectures rely on photonic subsystems able to assist, complement, replace and/or extend the capabilities of conventional RF subsystems including:

- Optical generation/distribution of microwave Local Oscillators (LO)
- Photonic RF frequency up and down conversion
- Routing of µ-wave signals in repeaters

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- Photonic assisted beam forming networks
- Optical sampling for analog to digital conversion

Optical modulators play a key role in the implementation of such functions.

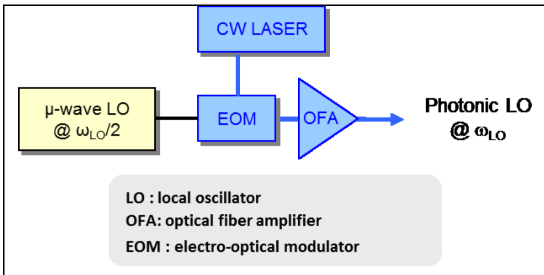

Figure 5: Microwave photonic Local Oscillator (LO) based on DSB-CS Schematic

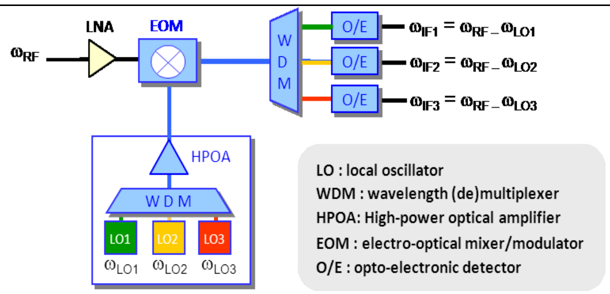

Figure 6: Optical Multi-Frequency Conversion concept

For instance, the optical distribution of LO's requires production of a microwave LO signal to be produced under optical form, with low phase noise and optical power high enough to be delivered to a large number of receivers while meeting system requirements. The transfer of a high-frequency signal onto an optical carrier through direct modulation of the laser current is not applicable at high frequencies, and requires external electro-optic intensity modulators. In particular, optical double sideband modulation with carrier suppression (DSB-CS) is an LO generation technique making use of a high-power CW laser and a MZ electro-optic modulator (EOM) biased at minimum optical transmission, as shown in Figure 6. When the modulator is driven by a microwave signal at ωLO/2 frequency, the optical output signal mainly contains the first two modulation side bands. Optical heterodyning at the photo receiver generates a microwave signal at the ωLO frequency.

Photonic RF frequency mixing for both up and down conversion of microwave signals can be achieved optically by means of EOMs. In addition to a very wide bandwidth and an infinite LO to RF input port isolation, a remarkable feature of electro-optical mixing is its ability to perform simultaneously multiple frequency conversions. In this concept, shown in Figure 2, the optical mixer is fed by several optical LO's through wavelength-division-multiplexing (WDM). In this way, the RF signal at the ωRF frequency driving the modulator is mixed to the different LO's and frequency- converted to several signals at various ωIF frequencies.

3 Environmental tests to obtain the space qualification

To obtain their visa for space, beside the specific performance required for each application, external optical modulators have to pass a comprehensive environmental test program which includes radiation tests, vibrations and shocks, vacuum operation tests, damp heat operation tests, temperature cycling, ESD tests, hermeticity tests, outgassing analysis, and destructive physical analysis (DPA)…
This is summarized in the chart given in figure 7 below.

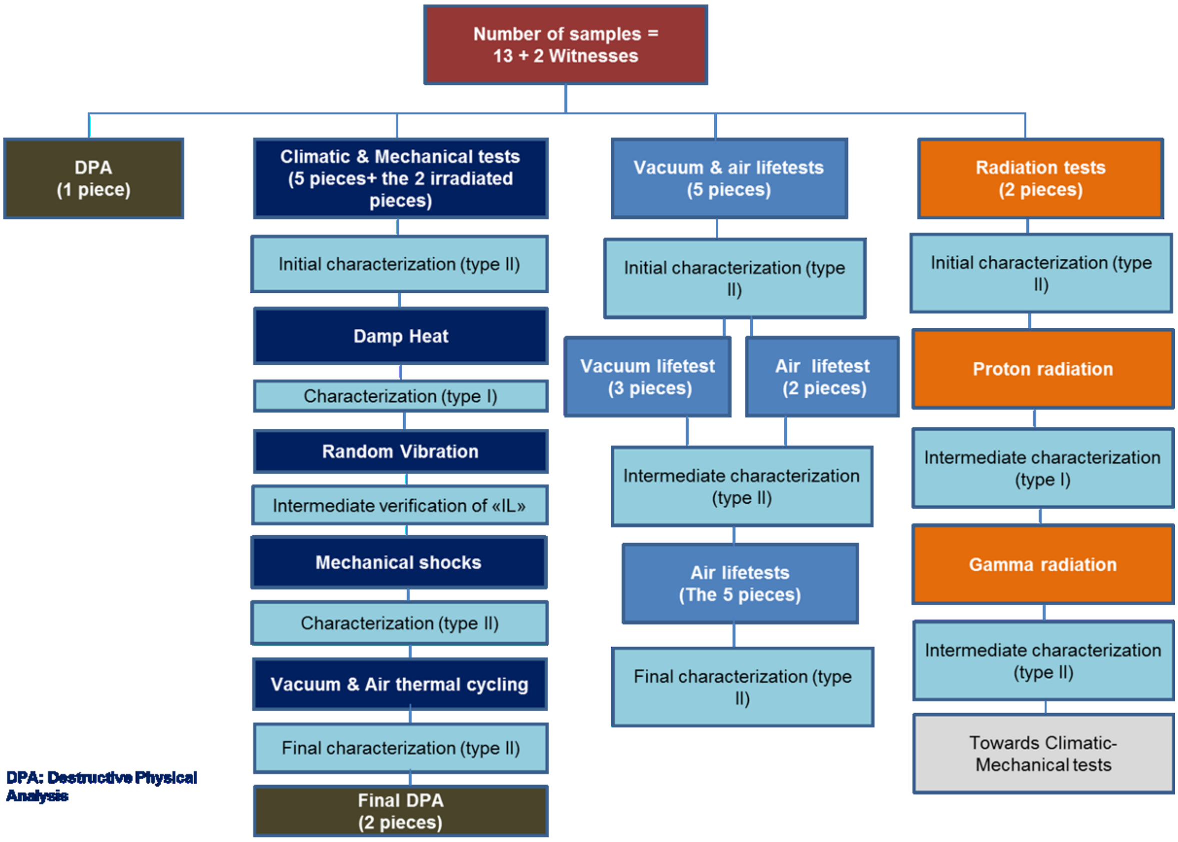

Figure 7: Example of evaluation of test program

4- Modulators for space at IXBlue-Photline

Over the past years, intensive design works and test programs have been conducted at IXBlue- Photline to improve the environmental performance of the modulators and to make them compatible with space applications.

In 2014, eight modulators were delivered to NASA: Two (2) of them are being integrated in the GRACE-FO tandem satellites and will fly in 2017, where they will join in space dozens of company modulators already operating in fiber gyroscopes.

In 2014 as well, IXBlue-Photline received a significant contract from TESAT-SPACECOM to design and deliver modulators for Laser Communication Terminals used for inter-satellite free-space communications.

Figure 8: A space compatible 20 GHz Intensity Modulator