International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

Edited by Bruno Cugny, Errico Armandillo, and Nikos Karafolas

DAS photonics developments for analogue and digital photonic links for intra-satellite communications

Julián Blasco

Eloy Rico

Pablo Genovard

Cristina Sáez

et al.

International Conference on Space Optics — ICSO 2012, edited by Bruno Cugny, Errico Armandillo, Nikos Karafolas
Proc. of SPIE Vol. 10564, 1056439 · © 2012 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309071

DAS PHOTONICS DEVELOPMENTS FOR ANALOGUE AND DIGITAL PHOTONIC LINKS FOR INTRASATELLITE COMMUNICATIONS

Julián Blasco (jblasco@dasphotonics.com), Eloy Rico (erico@dasphotonics.com), Pablo Genovard (pgenovard@dasphotonics.com), Cristina Sáez (csaez@dasphotonics.com), Olga Navasquillo (olga.navasquillo@dasphotonics.com), Javier Martí (jmarti@dasphotonics.com)
DAS Photonics, Valencia, Spain

Abstract—During past years, special efforts have been invested to develop optical links, both digital and analogue, for space applications, such as reference signal distribution or digital communication cables. The aim of this paper is to present the current DAS developments for these applications as well as future work to increase TRL levels and flight opportunities.

***Index Terms*— Microwave photonics, Radio over Fiber, Space communications, phase stability, phase noise, optical harness.**

I. INTRODUCTION

Currently, main space application suppliers have centered their efforts in developing a new generation of flexible payload systems for future larger scientific and communication satellites.

This new concept of satellite payloads requires high number of feeds or even phased array systems for multi-beam applications composed by high quantity of converters. In those applications, the frequency distribution networks could become a critical issue where optical links are considered as a promising alternative to traditional solutions.

Moreover, new generation of control buses or data links will be necessary, being optical digital links the best solution due to inherent benefits of optical fiber and photonics, such as:

- **Mass and size saving**
- **Cable management flexibility**: for those applications where a high number of cables shall be routed, optic fiber reduces size of cable bundle to be managed.
- **Lower optical fiber transmission losses**
- **Better phase stability** over temperature and when bent in comparison with coaxial cable
- **Low electromagnetic emissions** and absence of ground loops

For digital links DAS has developed a solution to substitute copper cables in satellite control buses application (MIL-STD-1553 or CAN BUS) and point-to-point links (i.e. SpaceWire).

After the completion of the TDP8 project, framed in the Alphasat mission, where DAS delivered a flight optical board with four optical transceivers for digital communications, DAS has worked in other ESA activities to evolve initial optical transceivers in a final product, including development activities and in-orbit validations for analog or digital optical links.

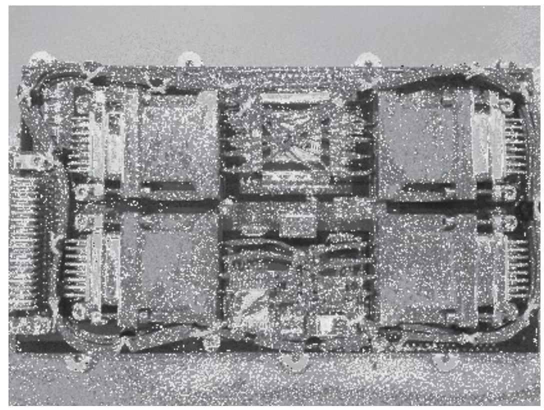

Fig. 1: DAS experiment in Alphasat TDP8

For analogue links, DAS has a wide range of solutions for ground segment covering high performance transmissions of signals from baseband up to frequencies in excess to 40 GHz.

Currently, DAS is involved in the development of similar optical links for different on-board applications, especially links to distribute reference signals that are commonly used in Telecom Satellite payloads. In parallel with the link development, an as part of the same activity, a complete verification campaign for the non-qualified components is being performed. The project will be culminated with a flight opportunity to validate the link performance in a real space environment.

Those photonic links shall meet the low phase noise requirements while ensuring drastic mass savings and suppressing isolation and EMC issues.

II. DIGITAL APPLICATIONS

The optical transceivers to substitute digital communications onboard developed by DAS Photonics have been designed taking into account the requirements of the most important protocols and communications systems used for intra-satellite equipments interconnects, such as:

- **Low Speed:** this solution, with a maximum data rate of 10Mbps, covers all control buses such as MIL-

STD-1553 and CAN. Also is suitable to substitute other low speed links such as TM/TC signals or even low speed clocks.

- **Medium Speed:** this solution, with a maximum data rate of 500Mbps, covers all SpaceWire data links (with low skew/jitter) usually used from 100 to 400 Mbps. Also is suitable to substitute other medium speed such a clocks or commands.

The most important components of the designed optical transceivers are the optronic devices and their drivers/amplifiers which allow reducing mass and optimize power consumption. For instance, using data collected from GAIA satellite and the complete description of the 1553 BUS, the bus harness mass reduction has been calculated greater than the 60% using an optical bus.

After Alphasat TDP8 project and under the ESA GSTP activity called Active Optical Cable (AOC), DAS Photonics has designed several models of AOC transceivers in order to adapt them to the current satellite protocols. The non-qualified components used in these transceivers, which have not been used in Alphasat project are being submitted to a devoted test campaign to assess their suitability for space applications.

In addition, the engineering models manufactured during the project will be submitted to a test campaign at module level (including mechanical and radiation tests) to validate their behaviour in space environment. Therefore, the qualification test campaign has been divided in two different parts, components and modules test campaign.

This campaign is expected to be executed during last quarter of 2012.

The results of the test campaigns part of the TDP8 Alphasat project were successful, confirming the suitability of the components for space environment. Therefore, similar results are expected for the new developments in AOC activity.

In addition, DAS has worked in developing a Techno Payload, which intends to validate in orbit a fiber optical cable developed by T&G Elektro.. Two optoelectronic conversion modules working at 100Mbps has been used to generate optical signals. The EBB, consisting in a fully representative FFF of the FM, has been successfully tested with Proba V interfaces and the flight unit will be delivered in October 2012.

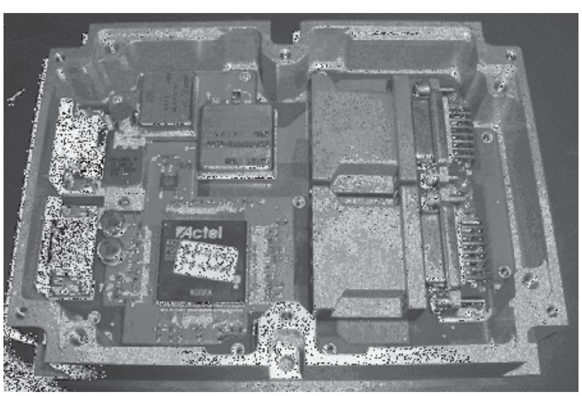

Fig. 2: HERMOD EBB for Proba-V IoV

III. ANALOGUE APPLICATIONS

To meet the demanding requirements for satellite reference signal at low frequencies, an optical DML (direct modulation link) is under DAS development in the frame of an ESA activity. Although the current design of the optical link will be able to work up to few GHz, the input and output stages have been specifically designed for low frequency reference signals. It exhibits very low figures for most critical parameters such as losses, noise figure, added phase noise; and very low phase and amplitude deviations induced by the space environment (EMC/EMI, temperature, radiation…).

The different optical components part of the optical links that are not space qualified are being submitted to an individual test campaign to assess their suitability for space environment. In order to avoid the risk of failure in the qualification test campaign, two options, baseline and backup, have been selected to be submitted to this campaign.

The same Qualification Test Campaign performed for digital optical transceivers components has been proposed in this case, it comprises the following tests; At component level: Constructional analysis, Residual Gas analysis, Thermal Vacuum Cycling tests, Thermal Conductance analysis and Outgassing test. At module level: Vibration, Shock, Thermal Vacuum Cycling Test, Radiation: TID and Radiations: Protons tests will be performed.

Finally, a representative configuration of an optical distribution unit is planned to be validated In-Orbit to have a complete characterization of the main performances of optical link and optical components in a real space environment.

IV. ANALOGUE SYSTEM DESCRIPTION

The in-orbit validation configuration defined by DAS will include one optical coupler (2:2) which distribute the reference signal from two EOCs (Electro-optic conversion module) to two OECs (opto-electronic conversion module).

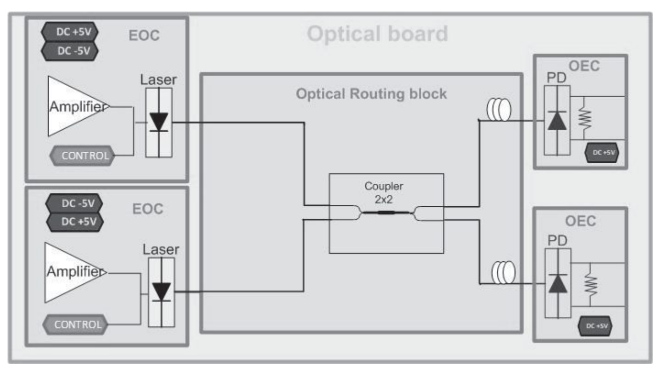

Fig. 3: Simplified block diagram

The optical link has been designed attending the main requirements of traditional reference signal distribution units for low frequency (around 10MHz), which are the most demanding.

Parameter	Min	Typ	Max	Units
Operating Temperature	-40	-	85	ºC
Power consumption	4		5.5	W
RF input power		10		dBm
VSWR @50Ohms		1.6:1	1.8:1	
RF link gain	-10	-0		dB
Added phase noise				
10 Hz 100 Hz 1 kHz 10 kHz 100 kHz 1 MHz 10 MHz		-130 -150 -157 -160 -161 -161 -161		dBc/Hz
Allan deviation (10s < τ < 100s)		$2\cdot10^{-12}$		
Amp. stability		±0.9		dB

Table 1: Analogue link, main specifications

A. EOC module

The optical link is composed firstly by an electro-optic conversion module (EOC), capable of translating the reference signal into the optical domain. Then, the optical signal can be transmitted and distributed through fiber, taking advantage of the high stability, capabilities and features of optical fiber.

The EOC (Electro-Optic Converter) module has the function of performing the electrical-to-optical conversion. The main building blocks for the EOC are:

- Laser diode: performs the electrical-to-optical conversion. Its control is critical to ensure optimal behavior.
- Amplifier: A biased BJT amplifier is used at the input in order to reach the necessary CNR to obtain as low phase noise as possible.

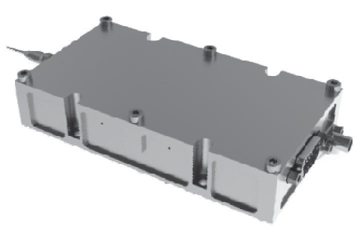

Fig. 4: EBB EOC module

1) Laser

A DFB laser is being used as the electro-optic converter, because its low noise, good stability and high available output optical power. These lasers require a complex control circuitry to ensure stability and low noise. Laser parameters such as its input impedance, output power, L-I curve, among others, determine the exact design of this control.

RIN (Relative Noise Intensity) parameter is critical, and it should be as low as possible, since it defines both, CNR and residual phase noise level [1].

DFB lasers dependence with temperature is a critical issue for this application. The efficiency of the laser decreases as the temperature increases, therefore the control circuitry must include some kind of temperature control. The selected laser package contains a Thermo-electric Cooler (TEC) that allows heating or cooling the laser when necessary, and therefore kept the laser critical parameters in line with the product performances within all the temperature range.

The main characteristics of the selected lasers are the following:

Op. Temp.	Po (dBm)	Ith (mA)	Imax (mA)	RIN (dB/Hz)	Total Max Power Consumption(W)
-40/+85ºC	≥13	30	190	< -150	4.0

Table 2: Laser main specs.

2) Amplifier

In order to achieve better phase noise performances a preamplifier stage is needed. A low 1/f noise transistor will be used in the EOC in order to achieve maximum input power at the target frequency.

B. OEC module

The Opto-electronic conversion module receives the optical signal after the optical distribution, converting it back to electrical domain where the signal will be amplified, filtered and applied to the receiver. The key components are the photodiode and the matching output circuit.

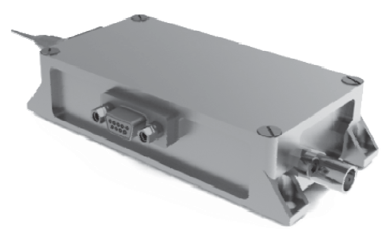

Fig. 5:EBB OEC module

1) Photodiode

In the same way that for the electro-optic conversion block, a detailed survey has been performed being following performances the optimal for the final product:

Packaging	Op. Temp.	BW (GHz)	Resp. (A/W)	Dark current (nA)
coaxial	-40/+85ºC	3	0.98	5

Table 3: Photodiode main specs.

Both photodiodes exhibit good responsivity and low noise, as well as high linearity and mechanical simplicity.

C. *Optical Distribution Unit*

FBT (Fused Biconic Tapered) Splitters have been selected, since they have already been used in other space projects (e.g. Fibre optic couplers assembly in MIRAS radiometer in SMOS satellite). This heritage will be very useful for defining and adapting environmental device's requirements to the ones of the current mission.

FBT is a low loss and robust technology with many years of qualification test history and excellent in-service history without failure for many applications and environments.

V. OPTICAL RF LINK ANALYSIS

The link design has been done in order to configure the laser bias in the optimum value, avoiding laser clipping and minimizing noise contribution, and using the input amplifier to increase the CNR of the system, reducing this way the impact of RIN, shot and thermal noise.

Optical output power should be in a region where RIN noise contribution is not dominant, obtaining then optimum CNR. Different noises can be calculated as [2], [3]:

$$N_{TH} = \frac{1}{4} 4\, k_B T\; BW$$

$$N_{RIN} = \frac{1}{4} RIN\; I_{DC}^2 BW \cdot R_L$$

$$N_{SHOT} = \frac{1}{4} 2\, q\, (I_{DC} + I_{dark}) BW \cdot R_L$$

All these issues have been studied and simulated to be sure that the optimum operating point for the current application is selected.

For a directly modulated optical link, the RF gain can be obtained according to the next expression, the optical link gain (G) and its noise contributions can be calculated as:

$$G_{link} = S_{21} = \frac{1}{4} \cdot \Re^2 \cdot \eta^2 \cdot \left(\frac{1}{Lopt}\right)^2 \cdot \frac{R_L}{R_s}$$

This parameter depends both on EOC an OEC optical parameters, but also on path losses. With no amplification, a typical link gain will be negative. Therefore, the amplifier has been biased to ensure optimal gain and minimum back-reflections.

VI. STABILITY ASPECTS

The optical link will be subjected to several sources of instability, both in amplitude and phase.

A. Amplitude stability

The temperature characteristics of the laser diode are such, that as the threshold current increases, the slope efficiency of the laser device decreases. This phenomenon makes the laser less efficient, reducing the RF signal gain and increasing the link noise figure, as well as causing additional degradation in the laser linearity.

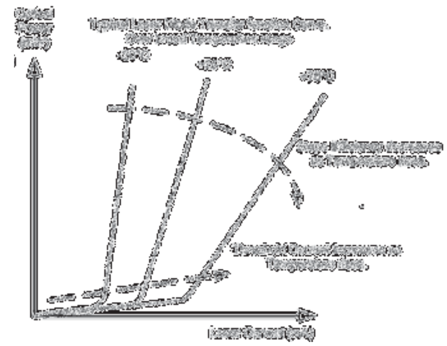

Fig. 6: *Laser transfer function curve over temperature range*

At the receiver side, the effects of temperature in the PD is a slight variation of responsivity (<2%). Moreover, Photodiode subjected to gamma and Proton irradiation [4] showed no significant change in responsivity and only a minor increase in dark current.

These effects will be assessed in orbit measuring the optical power at the output of the link.

B. Phase stability

For flight applications, temperature and radiation are the most critical factors affecting phase stability. Temperature affects both the optical link and the signal distribution unit (from the reference signal to the EOC).

In the optical link there are also sources of phase instabilities. Every DFB laser exhibits AM/PM conversion in some degree, and this affects directly the residual phase noise in the optical link. RIN parameter also has a direct effect on this added phase noise.

Moreover, amplitude noise in power supply also affects signal phase integrity at some offsets and should be studied. Phase deviation is also affected by chromatic and polarization dispersion in optical fiber, which depends on radiation and temperature conditions.

Allan Variance is a widely accepted measurement of frequency stability in time domain, since phase noise at small offset frequencies cannot be easily measured in frequency domain. Therefore, during the in-orbit validation Allan Variance will be measured to characterize phase stability.

To calculate this parameter, an in-orbit subsystem based on Dual Mixer Time Difference scheme will be developed by DAS, using two local oscillators to generate a downconverted signal which carries the relative phase between one branch and the other. Therefore, common noise is cancelled and only differential phase (coming from the optical link and the distribution system) is calculated.

VII. EXPERIMENTAL MEASURES

Some experimental tests have been done on the complete link, EOC and OEC to show that stability is fulfilled. Figure 5 and 6 depict the evolution of amplitude and phase for a variation in temperature (23ºC to 85ºC), obtaining a maximum deviation of 0.1 dB and 0.2 º, respectively. Associated Allan deviation is also depicted in fig. 7.

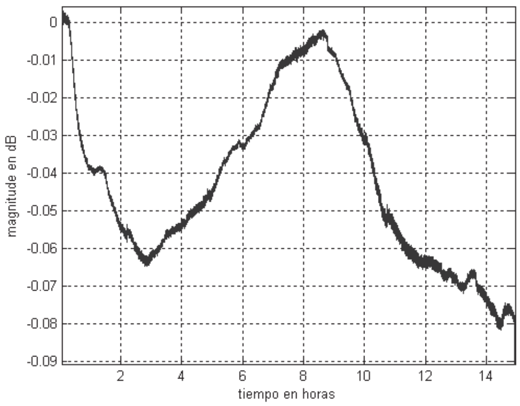

Fig. 7: *Amplitude stability (in dB) during 15h measurement*

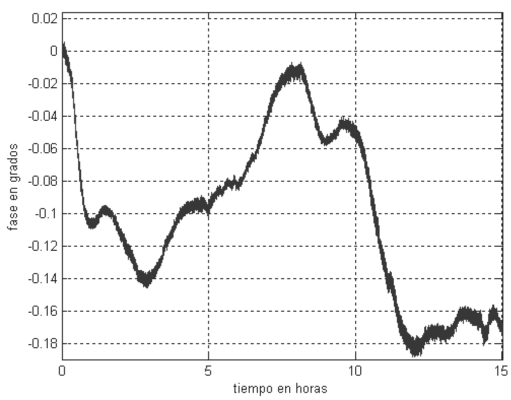

Fig. 8: *Phase stability (in degrees) during 15h measurement*

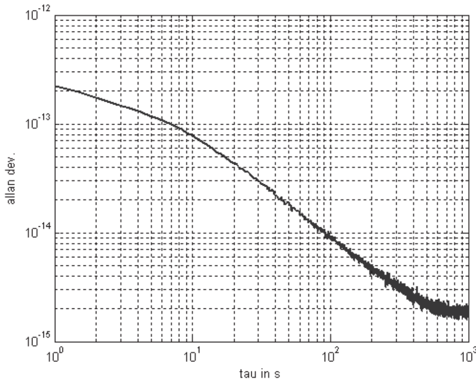

Fig. 9: *Allan deviation (1s<τ<1000s)*

VIII. FURTHER WORK

DAS further work in analogue and digital links for space applications will be oriented to increase the TRL levels for ongoing developments and upgrading them to recurrent solutions for current RF applications substitution.

On the other hand, DAS is acquiring experience as developer of fast In-Orbit validation solutions for optical products, being the Proba-V opportunity a good example. With a very tight schedule of six months for the delivery of the flight model, DAS has been able to, not only demonstrate the suitability of its digital optical solution, also to accommodate the digital transceivers with optical fiber for space applications.

IX. CONCLUSIONS

DAS Photonics analogue and digital optical links developed to replace copper transmission medium for space applications have been positioned as a potential alternative with high degree of suitability.

Benefits of the optical solutions have been demonstrated during the last years in several activities, but an in-orbit validation is necessary to verify the behavior in real environment and show that the units are operating in orbit.

Key optical components for analogue and digital modules are not space qualified. Therefore, a devoted test campaign is required for each component to verify their suitability for space use.

Measurements prove that analogue optical links are adequate for distributing reference signals, which require good phase and amplitude stability, as well as low noise figures. Final assessment will be done taking into account the final scenario.

X. REFERENCES

[1] B. Onillon, S. Constant, G. Quadri, B. Benazet and O. Llopis, “Low phase noise fiber optic links for space applications” 2005

[2] C. Cox, E. I. Ackerman, G. E. Betts, and J. L. Prince, “Limits on the Performance of RF-Over-Fiber Links and Their Impact on Device Design” IEEE 2006

[3] C. Cox, D. Tsang, L. Johnson, and G. Betts, “Low-loss analog fiber-optic links,” in IEEE MTT-S Int. Microw. Symp. Dig., Dallas, TX, 1990, pp. 157–160.

[4] Proton and gamma radiations effects on silicon photodiodes for space environments. Pedroza, G.; Gilard, O.: Bourqui M.L., Bechou L; How L.S; Rosala F.. ISROS 2009. Presentation