

Experimental Results of Free Space Optics WDM for Very High Throughput Spaceborne Terminal and Ground Station

R. Grasser^{*a}, M. Casale^a, V. Pollier^a

^aBertin Technologies, 155 rue Louis Armand ZI, 13290 Aix-en-Provence, France

ABSTRACT

During the early days of fiberoptics telecommunication development, data rate per line was limited to typically 10Gbps and the best way to increase throughput was to increase the number of lines. Wavelength Division Multiplexing (WDM) was therefore quickly adopted. Later came enhanced data format such as coherent coding that enabled a ten folds increase in throughput with the same number of lines.

Free Space Optics communications evolves the opposite way. Leveraging mature coherent coding, 100Gbps throughput is now the standard with a single line between satellites. But high throughput per line comes at the cost of the required power that rises faster than the link capacity. Hence, increasing the number of lines presents itself as a legitimate alternative toward Tbps link, however not straightforward. Indeed, power per line to reach 100Gbps is already about 10W in space and 50W on ground. This is well beyond typical levels stood by standard readily available fiberoptics components. As number of lines increases, so does the cumulated power and specific free space optics equipment must be developed.

We designed a High-Power MultipleXer (HPMUX) to handle this critical line merging step. It came with at least two hurdles related to the power level. First, beams diameter must be large to limit power density. This increases sensitivity to boresight and components misalignment. It has already been demonstrated that the suggested design can tackle this issue. Second and more subtle, the thermal load modifies the optical behavior of the components crossed by the beams. Based on latest experimental results we'll discuss here limitation it imposes on WDM deployment. We'll see that an HPMUX can work at kW level but remains sensitive to power load changes, making it optimum for a specific setting.

Keywords: WDM, free space optics communication, high throughput, high power, ground station, laser communication terminal

1. INTRODUCTION

Thanks to mature coherent coding (Quadrature Phase Shift Key – QPSK, or Quadrature Amplitude Modulation – QAM), 100Gbps throughput became a standard with a single line between satellites delivering valuable capacity[1]. To go beyond this standard with a single line requires complex coding, more computer resources and extra power[2]. This becomes acute in case of trans-atmospheric link that are subject to fading and requires extra margin. Optimizing link by always looking at best atmospheric condition among stations network is a valid option but limits the availability and predictability of high throughput links[3]. As in the early stage of fiberoptics for ground network, Wavelength Division Multiplexing (WDM) presents itself as the most effective way to increase throughput and availability without increasing power per line and computer burden [4].

However, going WDM in free space optics isn't straightforward. Indeed, power per line is already 37dBm on board and 40dBm on ground to close a 10GBaud link budget with GEO[5] and up to 46dBm for 100Gbps[6]. This is well beyond typical range stood by standard readily available fiber optic components. The natural answer is pictured in Figure 1. WDM is performed at low power with standard components, then the frequency comb is amplified all together[7][8]. That way, tedious free space optics is pushed at the very end of the optical train, keeping the light in the fiber everywhere else. Although simple, challenge on the amplifier is high. The power delivered is distributed among the lines. In order to get enough power per line, the amplifier capacity must be multiplied by the number of lines. Reliability of such system is low since failure of high end complex HPOA is likely and means failure of the link altogether. Furthermore, recent studies point out limitation of this approach to 3 to 4 lines because of four waves mixing non-linear effects and because the power an amplifier can deliver must be shared among the lines[9].

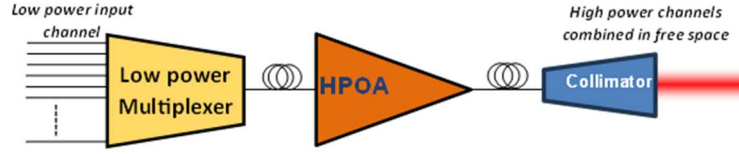


Figure 1: Typical WDM architecture using fiber multiplexer

Another approach is to reverse amplification and multiplexing, meaning each line is first individually boosted in power, then multiplexed in a bulk free space system. Figure 2 sketched the corresponding architecture. Compared with the first approach, reliability is greatly improved since failure of an HPOA means failure of only one line and not the entire link. 200GHz spacing at high power has been demonstrated using diffractive technology[10]. Complexity is however moved from the amplifier to the bulk free space optics multiplexer. And solution suggested are only suitable for ground station[10].

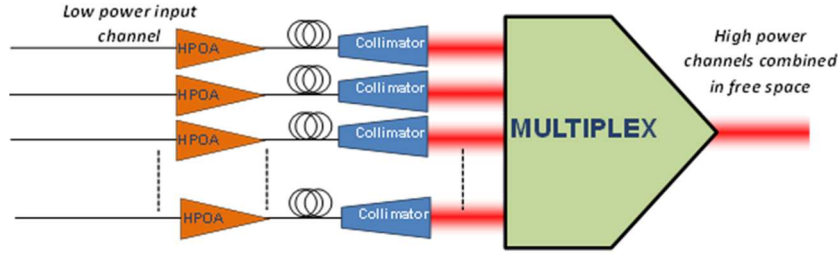


Figure 2: WDM architecture with free space optics HPMUX

2. HYBRID ARCHITECTURE FOR HIGH POWER WDM

Since few years, we worked on a hybrid approach using interleaver technology. We believe this takes advantage of both progress in amplifier performances and in bulk optical systems to reduce complexity and makes it suitable for both ground station and spaceborne operations[11]. The concept of hybrid architecture is represented on Figure 3. A step of pre-multiplexing happens first at low power by cluster of 2 to 3 lines. Each cluster is then individually amplified. The resulting boosted line clusters are merged with a bulk High-Power MultipleXer (HPMUX). This way, we keep the light in the fiber as long as possible until free space optics becomes mandatory.

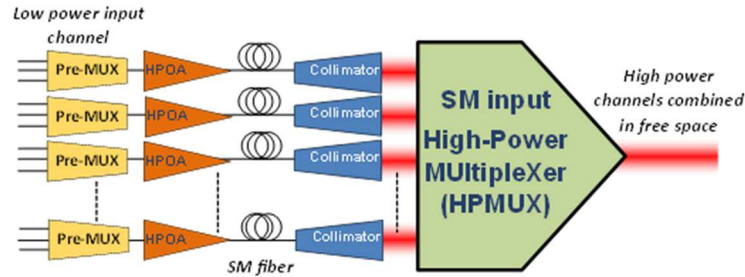


Figure 3: Hybrid architecture

For hybrid architecture to work, the HPMUX must be able to accommodate a set of lines coming together on each free space collimator. To achieve this, we suggest an HPMUX based on interleaver technology. This is explained on Figure 4. An interleaver building block puts together two combs of lines with a spacing of $2\Delta f$ into a single comb, twice denser, with a spacing of Δf . These building blocks can be stacked. The Figure 4 shows an example of 4 sets of 2 lines each multiplexed together into a single beam of 8 lines thanks to 3 stacked interleaver stages.

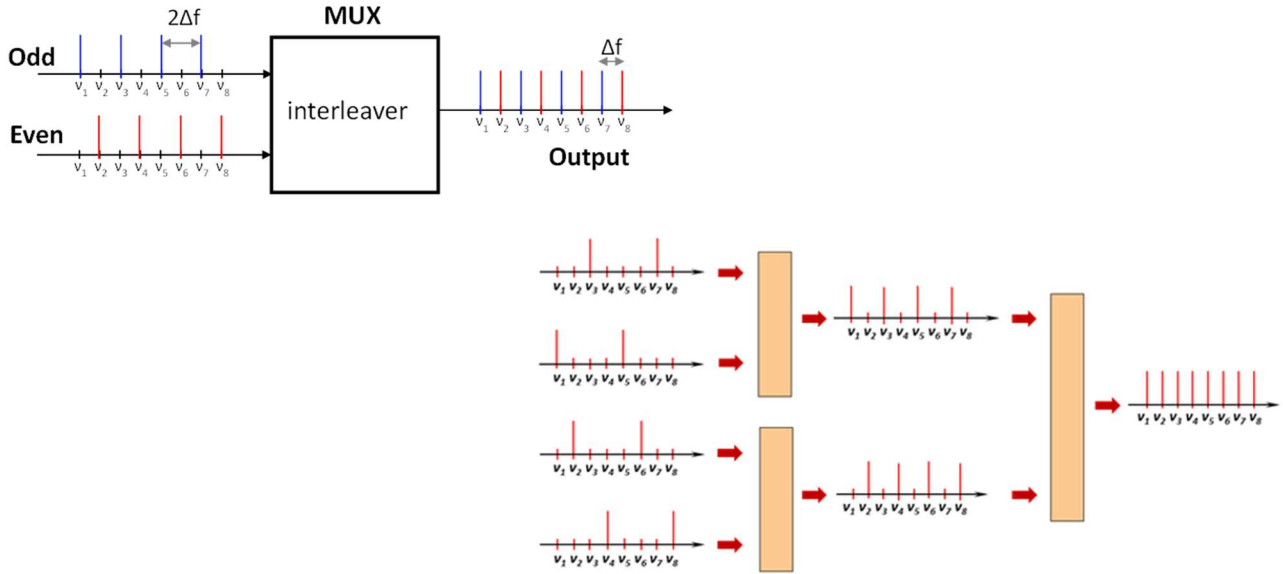


Figure 4: Interleaver HPMUX, single stage (top) and stages stacking (bottom)

Interleaver function is known in the field of passive optical components. Among the different ways to perform interleaver function[12], we choose the solution of Lyot filter, pictured on Figure 5, because easier to align and more resilient to power[11]. The two input line combs are merged via a polarization beam combiner (PBC) and the polarization is straightened up for all lines thanks to a Birefringent Crystal Assembly (BCA) acting as a Lyot filter.

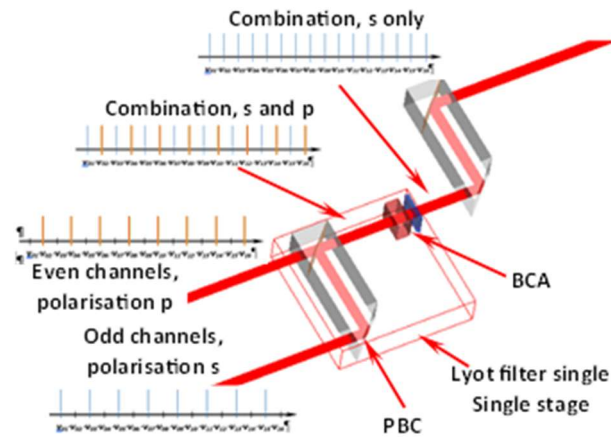


Figure 5: Lyot filter interleaver building bloc

No matter the solution, free space optics multiplexing comes with at least two hurdles related to the power level. First, beams diameter must be large to limit power density. Larger beams means smaller divergence and increased sensitivity to boresight and components misalignment. Multiplexing in free space comes down putting on top of each other many individual beams. It only works if all beams share the same geometry. Any alignment mismatch on one beam makes it go astray from the rest and signal is lost. Second, the thermal load modifies the optical behavior of the material crossed by the beams. This paper wishes to present the latest results for the hybrid architecture regarding optical performances under power load. We'll then discuss the opportunities it opens and limitations it imposes on WDM deployment.

3. EXPERIMENTAL CONFIGURATION

Thanks to the development and manufacturing of two mock-ups for the space and ground segments, it was possible to gather enough experimental data and hands one experience to understand performances and limitation of the HPMUX. For both ground and spaceborne version, a polarization split amplification is used. Sketched on Figure 6, fibered Polarization Beam Splitter (PBS) send 50% of the light to one amplifier and 50% to the other. Recombination happens inside the HPMUX. Split polarization amplification enables better HPOA performances with little data impairment[14][15][16]. Results presented here remain relevant in case of straight unpolarized amplification as pictured in Figure 3. Indeed, the multiplexing principle is the same in both configurations.

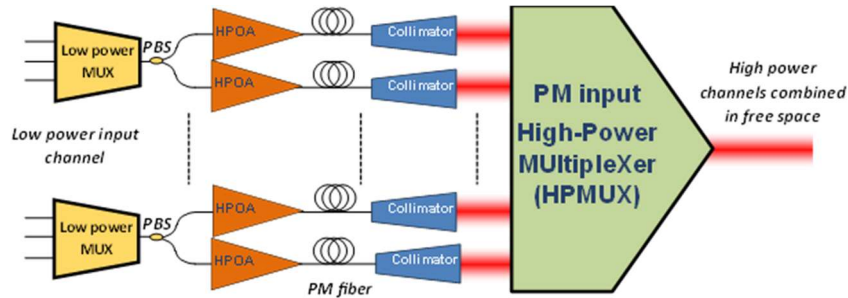


Figure 6: Polarization split architecture with WDM

Space segment

Top of Figure 7 pictures the spaceborne version of the HPMUX, configured for a final spacing of 125GHz. Beam diameter is 1mm in the free space part of the HPMUX. This helps on the SWaP and improves resilience to misalignment, critical in space where maintenance isn't possible.

Only one polarization arm is built. In a complete HPMUX, the other polarization is taking care of with the same structure, both polarizations being merged at the end. In this case, the HPMUX handles 4 linear polarized inputs carrying each 2 lines, 500GHz apart, all in the C-Band. Amplification per fiber delivers a power of 10W per fiber.

The bottom of Figure 7 sketches the experimental setup. For availability reason, only 2 fiber amplifiers (HPOA) have been used for the tests. Each are plugged on two of the four inputs. Because of high power, there's no connectors and fibers cannot be removed from the HPMUX without losing alignment. Both amplifiers are therefore definitely plugged on these two inputs. Seeders wavelength are adjusted to match the spectral grid of the HPMUX:

- On input 1, central wavelength is 1538.54nm (194855GHz) with insertion loss of -0.53dB at 10W.
- On input 3, central wavelength is 1549.48nm (193480GHz) with insertion loss of -0.50dB at 10W.

The two seeders are 1375GHz apart (11 channels spacing of 125GHz). Seeder 2 is tunable over 1nm and the OSA allows the measurement of the actual wavelength amplified. This will be used to scan the spectral response at high power.

Inputs 2 and 4 are both connectorized with FC/APC connectors. An ASE source can be swapped from one to the other.

At the output, the beam sampler send small portion of the light to a wavefront analyzer while the rest is sent to a thermopile for power measurement. A dichroic filter can also be added to isolate signal coming from input 3 from the one coming from input 1.

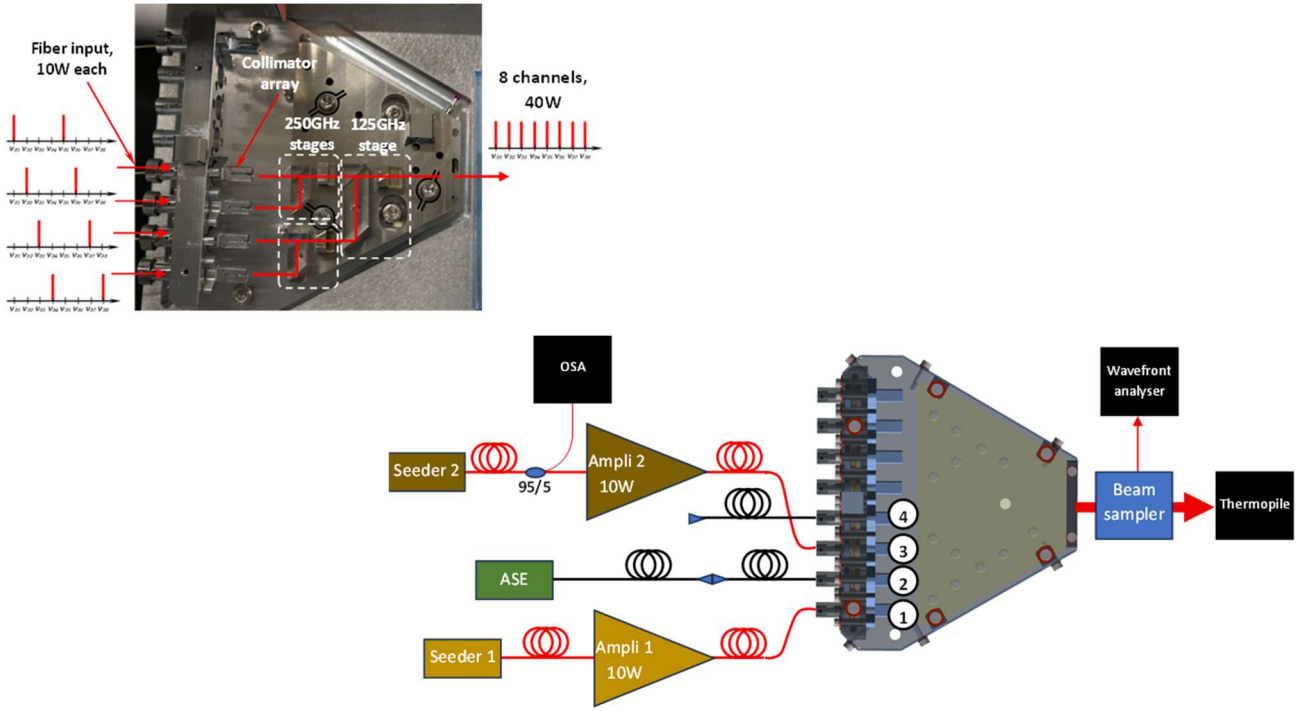


Figure 7: Spaceborne version of the 2x4 lines HPMUX (top) and experimental setup (bottom)

Ground segment

The ground segment HPMUX is bound to handle higher power than its spaceborne counterpart. Free space optics is therefore larger with a beam diameter of 10mm. Also, maintenance is an important feature enabling easy realignment or swapping of failing amplification stage. Collimators are therefore more complex, enabling active alignment, and comes with power monitoring function.

Figure 8 sketches the structure of the mock-up. 50W power signals are injected via fibers in each of the two collimators. Each have independent adjustment features enabling finetuning of the beams geometry as they leave the HPMUX. Each input are also monitored to send feedback to the amplifier on the level of useful power available.

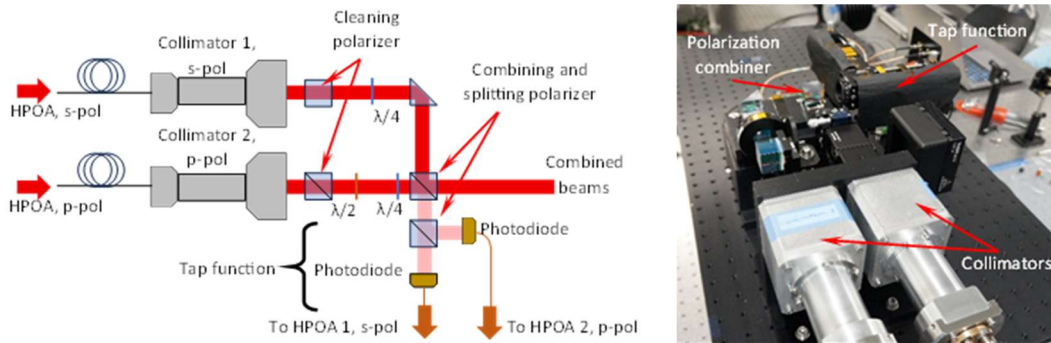


Figure 8: Polarization beam combination

For this work, the wavefront analyzer is placed at the output after a beam sampler to dim the power. This will help understand the effect of power on the collimator only.

4. RESULTS AND LIMITATIONS

The principle of free space line multiplexing function using Lyot filter has been demonstrated on the flight mock-up few years ago already[11][13]. Also, the resilience to misalignment and thermomechanical distortion have been extensively and successfully tested. Results showed good performances in terms of insertion loss ($<0.6\text{dB}$), spectral bandwidth ($>100\text{GHz}$ for spacing of 125GHz), isolation and beam geometric stability between the combined beams in free space: co-localization at 10% of average diameter, boresight at 10% of beam divergence and wavefront variation under 50nm rms among all the beams[17].

Because of its architecture, ground version (Figure 8) has been a good candidate for penalty evaluation on the signal when amplification are split between both polarizations. It has been the free space optical part of a test bed for the split polarization data transportation test campaign. Results have been published recently reckoning little penalty related to the dual polarization amplification[16].

These experimental results validated the Lyot filter approach. For instance, HPMUX spectral response is compatible with the telecom need and related penalty on the signal are low. And the beam merging technique in free space is robust enough to insure all beams are aiming to the same direction. The solution answers one of the challenge, which is the reliability of the multiplexing function at high power. The behavior of the different components under power load has been explored as well. And the results exposed in this paper are two folds.

Collimators sensitivity to high power: impact on beam focus

Using setup from Figure 7, we look at the wavefront evolution as power increases in each collimators 1 and 3 from 0 to 10W . Figure 9(a) plots the focus evolution and (b) the higher order aberration at the output of the spaceborne version of the HPMUX. Both increase versus power. Higher order aberration behavior is consistent with former measurement made on the Lyot filters alone [11][17]. In these former experiment, birefringent material of the Lyot filter have been individually tested under 100W power at 1550nm with beam diameter of 1mm . Results showed slight degradation of the wavefront as power increases, and we can conclude that most of the effect we see in Figure 9(b) are coming from the interaction of the power with the birefringent crystals of the Lyot filter.

On the other hand, focus evolution was much smaller at the crystal level when compared with the one present in Figure 9(a) for the complete HPMUX. Interestingly, results remains sensitively the same whether there is power in one or two collimators together. Wavefront variation is therefore mostly function of the power in the collimator and not of the power load in the Lyot filters.

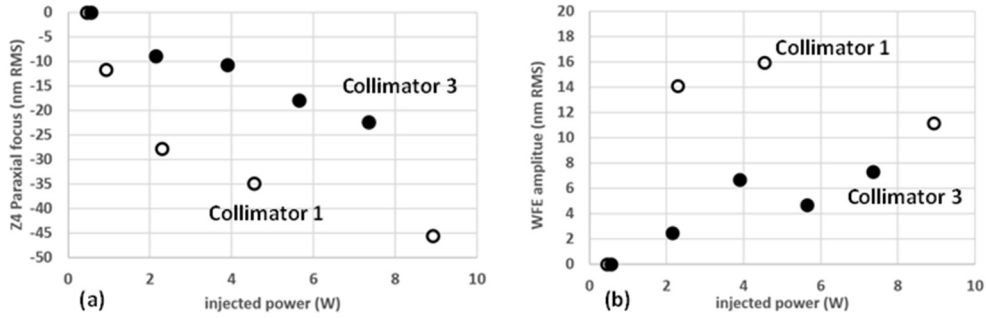


Figure 9: (a) Focus (Z4) and (b) residual wavefront evolution with power for two collimators

Using the gaussian beam propagation theory, one can estimate the spread of the beam at the receiver as a function of the focus changes at the transceiver. This simply lead to an attenuation τ_{Z4} of received power and a penalty in the link budget. Equation (1) gives the expression of τ_{Z4} vs Z4, the focus in nm rms according to the Noll distribution of the Zernike, and λ , the wavelength. It is therefore possible to translate focus evolution of the beam into losses in the communication channel.

$$\tau_{Z4} = \frac{1}{\left[1 + \left(\frac{4\pi\sqrt{3}Z4}{\lambda}\right)^2\right]} \quad (1)$$

In the similar way, the Strehl ratio formula tells by how much the Irradiance drops at the pick of the receiver as against the wavefront error WFE at the transceiver. Equation (2) gives the expression of the corresponding attenuation ratio τ_{WFE} as function of the WFE in nm rms and the wavelength λ :

$$\tau_{WFE} = \left[1 - 2 \left(\frac{\pi WFE}{\lambda} \right)^2 \right]^2 \quad (2)$$

Using these relations, Figure 10 translate the wavefront evolution on Figure 9 into losses. The impact inside the Lyot filter (Figure 10(b)) remains very small. But the focus evolution can generate losses up to 1.5dB (Figure 10(a)).

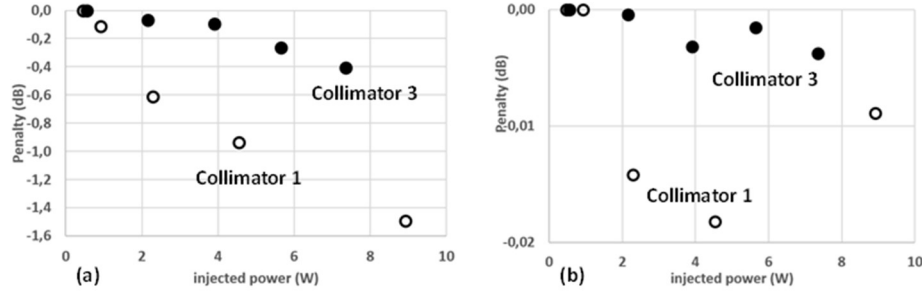


Figure 10: (a) focus related link budget penalty and (b) WFE residual error related link budget penalty

The wavefront analysis is also performed on the ground version of the HPMUX. Setup described in Figure 8 is used and Figure 11(a) plots the focus at collimator output vs power. Same evolution of the focus with power is clearly visible and penalty can reach 1.5dB against low power situation. But there's no Lyot filter in this experiment. The focus evolution therefore comes from the collimator. Figure 11(b) shows the temporal evolution of the focus as power fluctuate from 5 to 18W. The insert is a zoom on the first power switch, showing relatively fast focus change. This leads to a very localized thermal effect because of the fast response time.

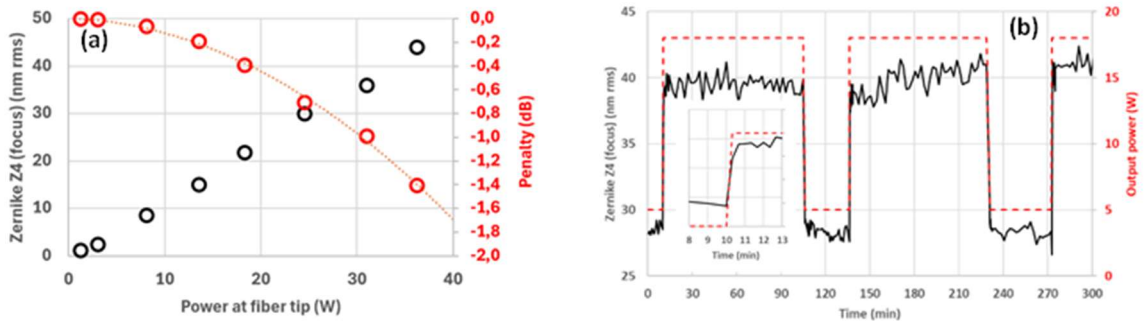


Figure 11: (a) focus value vs power and (b) focus evolution with time

Results presented in this paragraph point at the collimator rather than the Lyot filters. When looking at the collimator architecture, we reckon the focus change mostly happens at the fiber endcap where temperature can evolve rapidly. The endcap is a small glass rod that finish the fiber and let the light diverge in the glass before crossing the boundary with air of vacuum. This fiber ending is very useful to reduce power density on the first optical surface met by the high-power beam. But, since the light is still very concentrated, power density is high and temperature gradient can occur inside the glass. This creates a graded index effect as power crosses the endcap. The value of the thermally created lens can vary according to the power.

Lyot filters sensitivity to high power: spectral response dependance

The other important result to report is the shift of the spectral response with power. Setup sketched on Figure 7 is used with the seeder 2 being tuned in wavelength. The OSA tracks the wavelength sent into the amplifier and to HPMUX input 3. As the wavelength is scanned, output power changes with the spectral response curve showing a maximum value for the central frequency (1549.48nm / 193480GHz). The curve is traced for several power points from 1W to 10W.

Also, when the dichroic filter placed before the power meter, signal from input 3 can be isolated from input 1 (1538.54nm / 194855GHz). The spectral curve can therefore be recorded as the other amplifier is on or off. Figure 12(a) plots the spectral curve in this case. The scan is always performed on input 3 signal with the same power setting. The black curve is plotted with power on input 1 low. The same curve is plotted in red when the power on input 1 is max. The shift on input 3 comes from different setting on input 1.

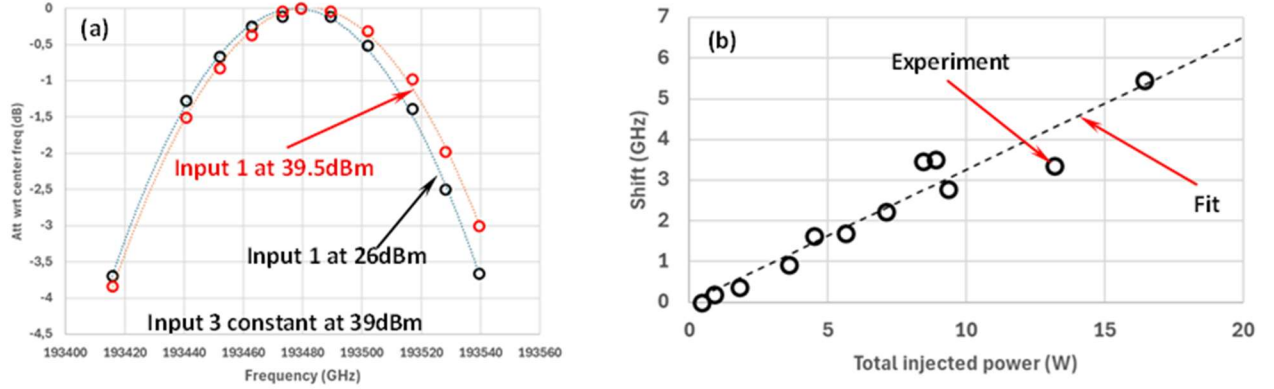


Figure 12: (a) spectral response shift on input 3 with two power settings on input 1 and (b) central frequency location vs. power on input 3

It's therefore possible to reconstruct the spectral response of the HPMUX on input 3 for different level of input power on input 1 and 3. Figure 12(b) plots the resulting central frequency of the spectral response as a function of the power injected in the HPMUX, all inputs included. This time, the shift is sensitive to the combined power injected in all collimators. The circles on Figure 12(b) are mix of shift measured with a single HPOA on or two.

Unlike wavefront effect, this shift happens inside the Lyot filters with an average of 0.5GHz/W.

5. DISCUSSION

The principle of the Lyot filter based HPMUX has been demonstrated and the architecture is sound in terms of alignment resilience to power. But the present work point two limitations, each linked to one component of the HPMUX.

At the collimator level, endcaps thermal sensitivity generates focus that depends on power. This effect isn't limited to the HPMUX. Any free space optics system eventually need collimator to move the light out of the fiber. Penalty can be significant if ignored. The best way to mitigate this effect is to adjust the collimator while crossed by high power. This will insure a proper behavior ones loaded. Still, penalty vs power curve shows a slope of about 0.1dB/W around high-power setting point. This means that power injected in a collimator should remain constant within few Watts.

Another trickier limitation happens at the Lyot filter. The BCA are designed athermal by mixing two materials that present opposite thermal coefficients[18]. It strongly reduces the thermal sensitivity of the BCA, but efficiency is reduced if temperature isn't uniform inside the BCA. Thanks to former material characterization[11], we know that one material absorbs more than the other and therefore heats more as beam passes through. The measurement of 0.5GHz/W implies a temperature gradient inside the BCA of $\sim 0.1^\circ\text{C}/\text{W}$. This has been backed by thermal models. A simple mitigation is to adjust and operate the HPMUX always at nominal power. But this reduces flexibility on power distribution.

6. CONCLUSION

This work presents the latest results on high power multiplexing for WDM in free space optics and focuses on the most relevant limitations. If there isn't structural limitation to work at kW level, wavefront and spectral response are sensitive to power load. Performances will always be optimum for a specific setting. As we move away, penalty occurs. Next steps of the development will be the optimization of the thermal management, in particular inside the BCA, to limit spectral response shift with power setting at the HPMUX input.

ACKNOWLEDGEMENTS

The work describe in this paper has been possible thanks to the strong support of the CNES (French space agency) through the France Relance Program. Next steps toward flight model are supported by the SOLiS program, part of the France 2030 Program, also led by the CNES.

REFERENCES

- [1] T. R. Brashears, "Achieving 99% link uptime on a fleet of 100G space laser inter-satellite links in LEO," Proc. SPIE 12877, Free-Space Laser Communications XXXVI, 1287702 (13 March 2024).
- [2] Y. Horst, B. I. Bitachon, L. Kulmet, J. Brun, T. Blatter, J.-M. Conan, A. Montmerle-Bonnefois, J. Montri, B. Sorrente, C. B. Lim, N. Vedrenne, D. Matter, L. Pommarel, B. Baeuerle, and J. Leuthold, "*This/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics*", Official Journal of the CIOMP 2047-7538, Light Science & Applications, 2023, 12:153.
- [3] O. Farley, P. Lognoné, R. Boddada, and J. Osborn, "Leveraging Network Diversity for Capacity Maximisation in European Optical GEO Feeder Systems under Realistic Optical Turbulence", in Proceedings Optica OFC 2026.
- [4] A. Maho, S. Levêque, A. Le Kernec, B. Benazet, A. Montmerle-Bonnefois, J.-M. Conan, C.B. Lim, J. Montri, P. Perrault, C. Petit, B. Sorrente, L. Paillier, N. Vedrenne, D. Metter, L. Pommarel, H. Lindberg, L. Francou, and M. Sotom, "*Experimental assessment of various optical communication chains for high-capacity optical feeder link*", in Proceedings SPIE, ICSO 2022.
- [5] Richard, Poulencard, Gnata, Coret, Anfray, Crosnier, Marduel, Zurawski, Montigaud, Lacoste, Sommer, Artaud, Benammar, Samain, Lanz, Bondoux, Montmerle Bonnefois, Petit, Vedrenne, Schimph, Forriere, "*In orbit testing of GEO feeder links with TELEO*", in Proceedings SPIE, ICSO 2024.
- [6] F. Maes, H. Limodehi, P. Katkov, Q. Peng, K. Deucker, P. Krauter, D. Fernie, P. de Villers, N. Mohammadi, K. Tagziria, F. Fischer, J. Kownatzki, F. Heine, and E. Haddad, "*100Gbps data transmission with 40W optical power amplifier validation for GEO-to-GEO data relay*", in Proceeding SPIE, ICSO 2024.
- [7] T. Schmitt, R. Cousty, T. Dumont, P. Morin, and F. Soulabaille, "*High power optical amplifier at 1.5 μ m for GEO and LEO optical feeder links*", in Proceedings SPIE, ICSO 2022.
- [8] A. Büttner, S. Hochheim, E. Brockmüller, W. Fittkau, F. Wellmann, P. Wessels, J. Neumann, and D. Kracht, "*Development of a highly-efficient amplifier system for 10 channel satellite laser communication in the context of the HydRON project*", in Proceedings SPIE, ICSO 2022.
- [9] S. Levêque, M. Gay, T. Chartier, A. Maho, M. Sotom, L. Bramerie, and M. Joindot, "*Assessing nonlinear effects in high-power optical amplifiers for WDM FSO communications up to 200Gbps per channel*", in Proceedings IEEE, ICSOS 2025.
- [10] F. Silvestri, L. W. Feenstra, F. Pettazzi, J. R. Nijenhuis, J. de Vreugd, D. de Bruijn, R. den Breeje, W. A. Klop, and I. Ferrario, "*High-Power Free-Space Bulk Multiplexer for Satellite Communication Optical Ground Station*", in Proceeding SPIE, ICSO 2024.
- [11] R. Grasser; M. Casale, R. Malifaud; V. Pollier; I. El-Ghazi; G. Aulanier; "*High power wavelength and polarisation multiplexing solution for space and ground stations applications*", in Proceedings IEEE, ISCOS 2023, Vancouver, Canada.
- [12] Li, Guo, Gu, "*Interleaver technology review*", Oplink communications, Inc. San Jose, CA USA, Proceeding of SPIE Vol. 4906 (2002).
- [13] R. Grasser, R. Malifaud, M. Casale, E. Compain, "*Low SWaP spaceborne Fiber to Telescope Terminal (FiTT) for high efficiency optical feederlink*", in Proceedings SPIE, ICSO 2024, Juan-les-Pins, France.

- [14] V. Billault, S. Levêque, A. Maho, M. Welch, J. Bourderionner, E. Lallier, M. Sotom, A. Le Kernec, and A. Brignon, “*Optical coherent combining of high-power optical amplifiers for free-space optical communications*”, Optics Letters, Vol. 48, No. 14/15 July 2023.
- [15] Y. Horst, L. Kulmer, T. Blatter, J. Winiger, V. Billault, G. Dandé, J. Bourderionnet, A. Brignon, A. Maho, Matthew Welch, S. M. Koepfli, and J. Leuthold, “A 100W Output Power Coherent Transmission Link for Future High Data Rate Earth-to-Satellite Communication”, in Proceedings Optica, OFC 2024.
- [16] R. Boddeda, E. Dutisseuil, D. Umasankar, S. Bordais, M. Casale, V. Pollier, R. Grasser, K. Guesmi, L.-D. Haret, S. Bigo, “Design and validation of low penalty high-power (>50W) optical amplifier for satellite communications using commercial coherent transceiver”, in Proceedings Optica, ECOC 2026.
- [17] M. Casale, F. Luga, V. pollier, R. Grasser, “*Spaceborne demonstrator of High Power Wavelength Multiplexer for Very High Throughput Satellites Optical Communication*”, in Proceeding IEEE, ICSOS 2025, Kyoto, Japan.
- [18] R. Grasser, M. casale, “Free Space Optical Beam Multiplexing System and Associated Method”, US Patent application 19/486,742, international filing date May 16th 2024.