Optical Satellite Communications

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Abstract

We aim to present the benefits and drawbacks in satellite to satellite and earth to satellite communication of optical systems (*Free Space Optics)* with respect to the most widely used RF; we'll explore the system structure and the challenges of it, and explain why this technology could take over RF in spatial communications.

I. Optical Vs RF communication

FSO technology is far less developed than the RF systems, but brings significant benefits along with limited drawbacks; to get a full comparison we can refer to the following table [1] :

TABLE I: FSO Vs RF

Characteristic	***FSO***	***RF***
Spectrum	Near infrared and visible light	Ka,Ku, mm-wave band
Bandwidth	in THz	in GHz
Wavelength	in nm	thousand of times larger than the optical one
Antenna size	smaller,$\simeq \lambda$	Much bigger
Beam Spread	Much narrower	typically 1000 times more
Directivity	very high	very low
Power Consumption	More power recived for a given transmitted power	Less recived power for a given transmitted power
Security	High due to directivity	easy to intercept
Interference	Almost non due to very narrow beam width	severely degrade performance
Solar Radiation	Degrades performance	unaffected
Line-of-sight Obstruction	Severely impact performance	Severely impart only in the mm-wave band
Spectrum regulation	unlicensed	licensed

We see how FSO systems provides good performances compared to classic RF, having limited drawbacks. In our context this technology applies to a new generation of satellites that will take into account constraints for implementing FSO onboard. As the trend for the new generation of satellites is to prefer Low Earth Orbits (LEO), line-of-sight with eart base station(s) is a key factor in orbits design. Aiming is another technological challenge, again related to orbits.
With respect to RF, FSO suffers solar radiation interference, for this reason the wavelength selectivity of receiver, and so it's robustness and reliability over many aspects (thermal, EMC), has to be carefully considered, tending to an overall strict requirement.

A big advantage in Space-to-space (or inter satellite links, ISL) communication is that there is no atmosphere, thus a series of detrimental effects, such as fading and scintillation, on channel is erased; for earth-to-space (E2S) communications we still have to consider atmosphere propagation channel.
Keeping line of sight is among the most difficult tasks; this will be later discussed.

A big advantage to consider is that existing technological platform for fiber optic communications in C-Band is reused in this context, exploiting low cost of supply chain, big set of data and in general a quite mature industrial context; For intra-satellite this is no problem, but for earth-to-space studies demonstrated how C-Band is not the best choice in terms of attenuation and detrimental effects from fog,rain and atmospere in general, and far infrared in the $9\mu m$ region would be a better choice [15]. We present a solution that is valid for both IIS and E2S applications, so standard C-Band is considered.

II. System Design

So first of all we need to know the transparent window of the atmosphere, this depend of the satellite type, but as they all have to communicate back to earth, this means that the second and third window are our target.
Chosen the window of operation we need a very stable optical source; we need to ensure the lowest possible back-reflection and maximize the reliability of it, then we need to modulate the signal; the modulation format is very important as we get a lot of interference from the sun, and considering dual use (ISL and E2S) thus having atmosphere, very dense format like 16-QAM or higher are not feasible right now; a simpler modulation format has to be chosen, popular formats are DSPK and DQSPK.
In figure we reported a basic block diagram of the system,in reality we need optical beam stabilizer (OBS) as we need to control the angle of the beam, also we need to control the collimation and focal plane alignment in order to reduce insertion losses, on top we need of coarse a feedback control circuit to maintain every part in its optimal working point, a more detailed analysis can be seen in [8],[10], as we want to focus on modulator,demodulator and receiver.

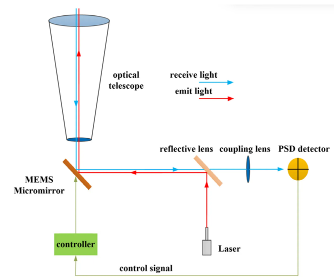


Fig. 1: Simple block diagram of the optical system

III. Receiver and Modulator

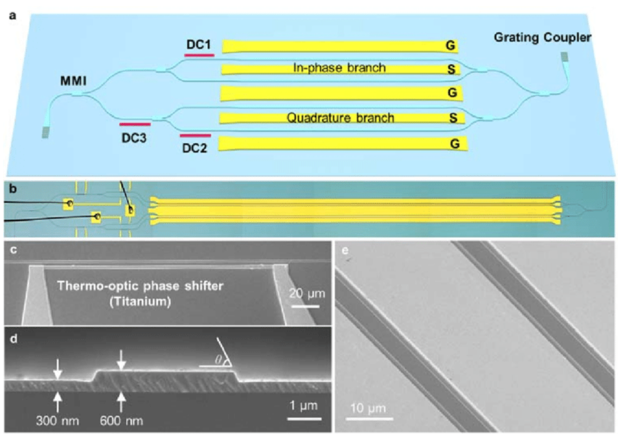


Fig. 2: [5] QPSK modulator

Among all possible modulation formats that have been used in FSO research projects, DPSK and DQPSK are good compromise of performance, reliability and implementation simplicity [4]. Such modulators are realized using phase modulator in combination with Mach-Zehnder interferometers. An emerging platform for realizing such modulators could be *Thin Film Lithium Niobate on Insulator* (LNOI) achieving better voltage-bandwidth performances [5]; this platform is not as consolidated as $LiNbO_3$ and is still in heavy development phase. This modulator achieves large bandwidths ($> 67Ghz$) over all C-Band, yelding to $100Gbaud$ corresponding to $200Gbit/s$ and $400Gbit/s$ bitrates (DPSK and DQPSK) with $BER < 10^-9$. Overall length of device is $15mm$ and maximum driver voltages are $7.5V$ (for biasing) and 1.9 (max V_π). Measured $ER > 25dB$.

In figure (3a) is shown a simple demodulator for DPSK [6]; this design is compact as does not require optical local oscillator.

Turbulence is manifested in phase contributions that are not uniform over the section of beam; as the beam propagates, both it expands and accumulates different phase for different spatial position. Upon reaching a photodetector, the sum of all contributions gives noise thus degrading SNR. In figure (3b) is shown a prototype of turbulence-compensation POP realized in SiP (*Silicon Photonics*) technology. After collimation, beam is coupled inside chip with different gratings, then numerous Mach-Zehnders provide phase shift to each path in order to compensate turbulence. Such system has to be controlled in a closed loop with high-speed electronics (FPGAs are commonly used) and features many heater for control, resulting in heavy power consumption (and thermal dissipation), much greater than one of the receiver itself. Thermal budget has to be taken into account especially for space-borne systems where heat dissipation is limited to radiation.

Such turbulence compensation device could be integrated on the same substrate as the receiver, providing an embedded receiver and demodulator realized in SiP.

Variable attenuation is given by environmental conditions: rain, fog, clouds and solar radiation change randomly giving variable attenuation; this can be mitigated by algorithms on RX side [9] but the choice of DQPSK scheme is intrinsically resilient to such phenomena. If choosing to operate higher order modulation schemes (i.e. M-QAM), such algorithm would play an important role in keeping system performances reliable over atmospheric variations.

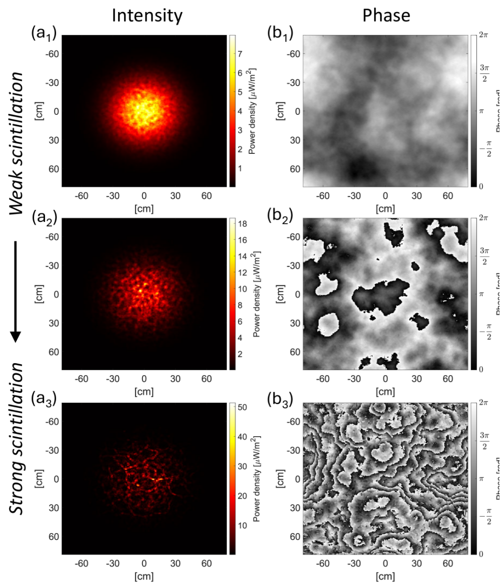
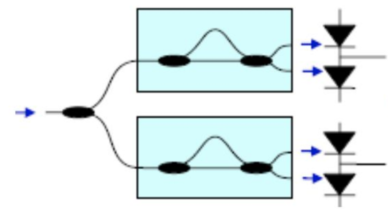
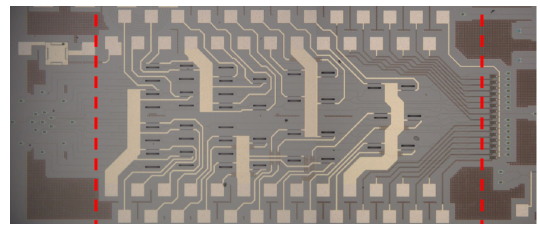


Fig. 3: [7] Turbulence and scintillation pheonomena (Intensity and phase)



(a) [6] DPSK receiver



(b) [7] POP for turbulence compensation

IV. Direction for improvements and future application

As we have seen the technology is still in an unripe phase, but there is growing interest as this could be key technology enabling faster space communication; possible applications include *Deep Space Optical Communication (DSOC)*,[11] where NASA has shown an interest in FSO for earth-to-space communication systems and it's currently testing this technology. An effective large-scale deployment of ISL has been achieved by *SpaceX* with it's *Starlink* constellation [14].

As for earth-to-satellite communications the challenges ahead are similar, one of the most critical point is to be able to pass trough the atmosphere in a reliable way, so a lot of interest has been generated in receiver and in it's sensors; an example of receiver to counter act the atmospheric interference was presented in the previous section [7]; another important breakthrough was the *Superconducting Nanowire Single Photon Detector* (fig 4), as it is the closest detector to an ideal SPAD.

This is a very recent development in the sensors scene, and has rapidly surpassed every other sensor in it's optical region; by implementing this kind of devices in an receiver architecture that exalt its strong points and minimize the atmosphere effect we could be close to a low power optical transmission in free space both in earth-to-earth and earth-to-space communication. Moreover the ideal scenario will be to go down to single photon communication, as this would guaranties the most secure transmission of data, but for all the reasons we cited before this is very unlikely, even if the evolution of detectors is aiming in this direction.

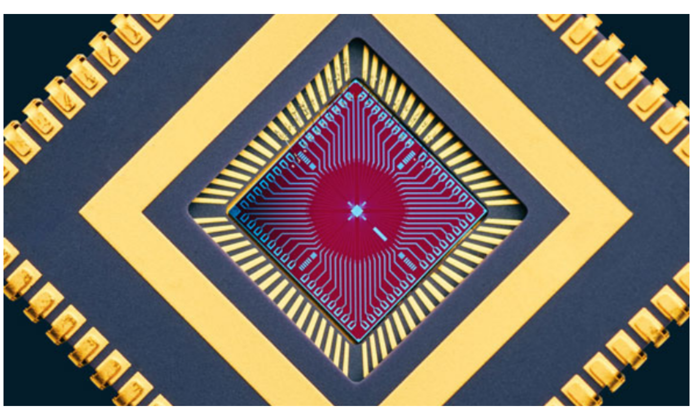


Fig. 4: tA 64-pixel SNSPD array

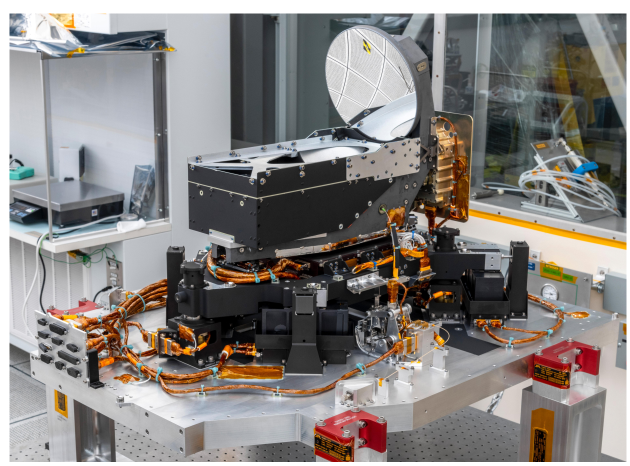


Fig. 5: NASA Prototype transreciver

V. Conclusion

FSO is overall a promising technology. Its intrinsic security, given by high directivity and non interceptability, combined with use of unregulated spectrum plays a big advantage with respect to RF communications. The quality of photonic components (modulator, demodulator) and mechanical systems (OBS) have to be really high, as well as the relative electronics control circuitry. Overall this technology will not become cheap in a short period, but presents strategic advantage to space applications, enabling low latency/high throughput between satellites and down to earth, that would otherwise require massive allocation of RF spectrum. Moreover new breakthrough in technology development could amplify the benefits; anyway we have to remember that RF systems have almost 80 years of development, while FSO is a much younger concept but still we can highlight how this technology is almost already surpassing the former over a lot of aspects.

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