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Stabilized Miniature Photonic Link for Space Applications

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Program: Spontaneous Concept

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Tutorial Introduction

Abstract

The space qualified compact inexpensive ultra-stable photonic links play the critical role for the frequency and time distribution since NASA has been planning more and more deep space exploration missions (for Mars and beyond, space telescope, radio science research, quantum links etc.). Some modern science-oriented flight missions (like Cassini's radio science research and gravitational wave searches) [1] call for extremely stable frequency transfer over the network. The next generation DSAC mission calls for a photonic link supporting the relative frequency stability of 10^{-16} at 1 hr averaging.

Based on the principle of phase conjugation, JPL Frequency and Timing Advanced Instrument group has developed a compact, phase stabilized Photonic Frequency Distribution (PFD) link that reduced the size by 11 times, from a 44U rack to a 4U chassis (Fig. 1), and kept same performance as the original equipment but significantly improved the SWaP and reduced cost.

Fig. 1. Phase Conjugation Module (4U chassis) vs SFODA. The size reduced by 11 times

Problem Description

a) Context (Why this problem and why now)

The space missions required not only the high quality performance (sensitivity, stability, flexibility, and so on), but also less SWaP. The explorations of Mars and interplanetary are requiring more and more stable frequency / timing standard, and higher data rate transmission, which the traditional RF approach won't be able to handle it. The phase fluctuation of DSN network caused by the temperature change limited NASA's deep space and interplanetary exploration missions.

b) SOA (Comparison or advancement over current state-of-the-art)

In this Task, per objectives identified in the proposal, we performed an R&D trade study effort focused on the advancement of the half-century old technology to a new level capable of meeting the requirements of the modern flight missions and other astrophysics research. We compared the performance of the free running and stabilized optical links and have shown that the stabilized links are suitable for time transfer of signals produced by emerging Deep Space Atomic Clocks.

Besides the SWaP reducing, we may replace the photonics components with PIC (Photonics IC) based function modules (laser / transmitter, optical circulator / switch, photonic receiver front end, etc.). So the size (therefore the entire SWaP) will be reduced more, which will make the stabilized photonics link ride on spacecraft possible.

We also studied a possibility of expansion of the idea of the stabilized optical fiber links to free space communications. We have developed a draft of proposal for NASA ROSES and plan to submit this proposal next year. A New Technology Report is also under preparation.

Problem Description

c) Relevance to NASA and JPL (Impact on current or future programs)

We have reviewed and analyzed a stabilized photonic link. Based on the analysis results, we presented a novel idea to open a new photonics approach – the Stabilized Miniature Photonic Link for NASA's space mission applications, which will improve the transmission quality, reduce the SWaP and cost. The next step will be identification of a NASA project to support development of the links. We are going to find new optical components to enable a new generation of the links, e.g. chip scale optical circulators and other integrated optical components to replace the link components and make the link as a unique photonics transmission system. We will design top performing links for the upcoming space missions since all onboard optical links for missions similar to Shuttle Radar Topography Mission (SRTM), the DSAC mission follow-on, etc.

Methodology

a) Formulation, theory or experiment description

The operation principle of a phase conjugation system may refer to the block diagram shown in Fig. 2. If we keep relative phase relationship at Point A and Point B as: (F_S-F_D) and (F_S+F_D), it is called as conjugated phase. Therefore at the midpoint (remote end), we have:

$$\Phi_M = (\Phi_S - \Phi_D) + [(\Phi_S + \Phi_D) - (\Phi_S - \Phi_D)]/2 = \Phi_S \qquad (1)$$

which is independent of the change of F_D.

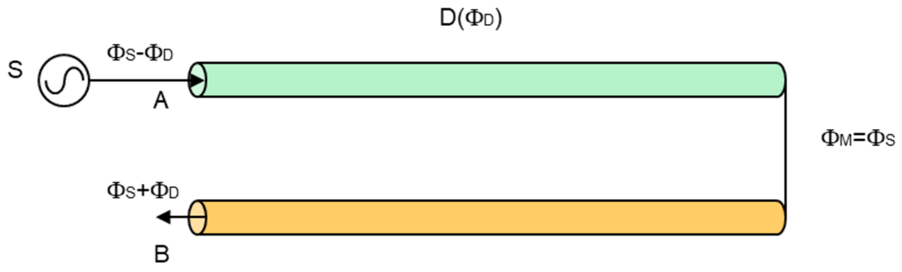

Fig. 2. Phase conjugation relationship

Methodology

With noisy VCO, optical transmitter and receiver, we have

$$\Delta\Phi_M = \Delta\Phi_V + \Delta\Phi_T + \Delta\Phi_R \quad (2)$$

Usually $\Delta F_T >> \Delta F_R$, therefore, the system noise performance will depend on the VCO and laser noise (Fig. 3):

$$S_M(f) = S_V(f) + S_T(f) + S_R(f) \quad (3)$$

$$\approx S_V(f) + S_T(f) \quad (4)$$

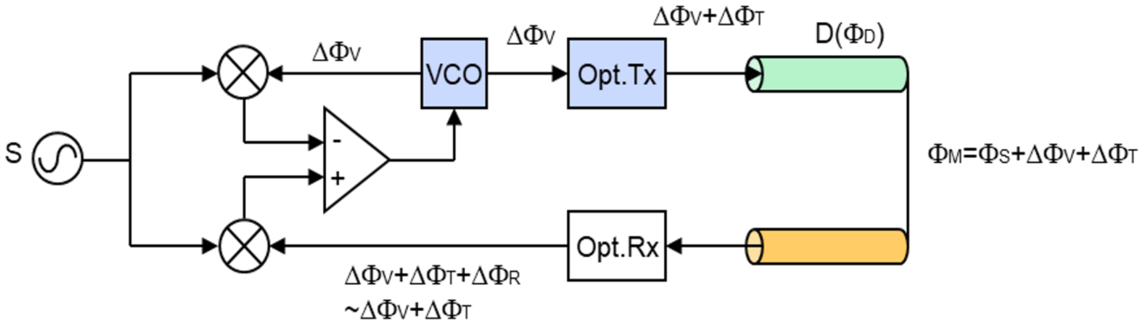

Fig. 3. Block diagram of a real phase conjugation system

Methodology

A photonics stabilized phase conjugation chassis has been built (Fig.1) according to the analysis above, which may achieve an over 200x stability improvement from 1E4s (2.8hrs) and beyond with chamber temperature cycling at ΔT=15 ℃ (Fig. 4). For the photonic parts replaced by PIC (Photonics IC) based components, the entire chassis size will be reduced much more.

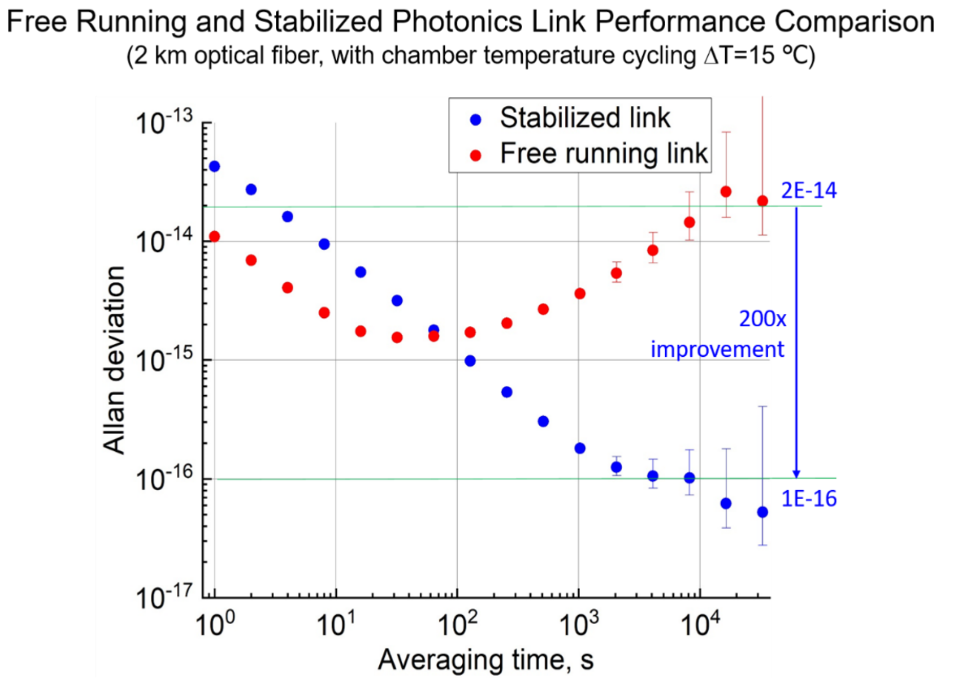

Fig. 4. Phase Conjugation Photonics Link Allan Deviation, 2 km optical fiber, with chamber temperature cycling ΔT=15 °C, over 200x improvement from 1E4s (2.8hrs) and beyond

Methodology

b) Innovation, advancement

Our study clearly show that the stabilized photonic link is ideal for the time transfer in space. It can support the best space clocks. For the phase stabilized photonic chassis (Fig. 1), we may replace the photonics components with PIC based functional modules (laser / transmitter, optical circulator / switch, photonic receiver front end, etc). So the size (therefore the entire SWaP) will be reduced more, which will make the stabilized photonics link ride on spacecraft possible.

Results

a) Accomplishments versus goals

Our study clearly show that the stabilized photonic frequency distribution (PFD) is ideal for the time and frequency transfer in space. Since its size is over 11 times smaller than the regular link, which will course the entire SWaP and cost been significantly reduced. It can be used for supporting the best space clocks and other space missions.

b) Significance

Based on the SWaP reduced phase stabilized photonic link, we may replace the photonics components with PIC based functional modules (laser / transmitter, optical circulator / switch, photonic receiver front end, etc), which will make the stabilized photonics link ride on spacecraft possible.

c) Next steps

We will try to more deep research and development on PIC based functional modules, use PIC modules to replace current photonics components, so make the stabilized PFD more close to NASA’s flight mission applications.

Publications and References

PUBLICATIONS:

A paper “A Stabilized Miniature Photonic Link for Space Applications” for IEEE 2021 International Microwave Symposium (IMS2021) is under preparation

REFERENCES:

[1] M. Calhoun, R. Sydnor, and W. Diener, “A Stabilized 100-Megahertz and 1-Gigahertz Reference Frequency Distribution for Cassini Radio Science”, Jet Propulsion Lab, IPN Progress Report 42-148, Feb. 15, 2002.

[2] L. Chen, Y. Guo, X. Shi, and T. Zhang, “Overview on the Phase Conjugation Techniques of the Retrodirective Array”, International Journal of Antennas and Propagation, vol. 2010, doi:10.1155/2010/564375.