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Intra-spacecraft optical communication solutions using discrete transceiver

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Abstract: The ever-decreasing size of the small satellites with more demanding payloads has opened new research areas to investigate innovative onboard data handling solutions. The paper presents the use of optical intra satellite communication using discretely designed transceivers. The transceiver can handle large variations in the received photocurrents and implements filtration against the ambient light. The designed transceiver has been tested with selected optical components including infrared diodes, photo detectors and optical guides to validate its functionality. The displacement damage testing on selected optical components was performed to validate their suitability for use in space. The experimental communication schemes have been presented for free space as well as glass fiber based intra spacecraft communication.

1. Introduction

The research and development on the low cost small satellites is on the rise since they are affordable with fast development times. The use of novel design techniques of platforms and instruments has made it possible to implement challenging missions with impactful scientific values. In the current new space era, the commercial value of the small satellites has become quite evident and many small-scale industries have emerged in the design and use of small instruments on such satellites for commercial services.

The advancement in the payload technology has also brought a tremendous increase in the data volumes with small satellites. The future small satellites, e.g. SAR satellites will require tremendous amount of data volumes to be handled at relatively high speeds. Therefore, the innovative communication solutions become obvious choice for future missions.

The harness mass in the traditional wired communication puts a trade off since it can account for up to 7-10% of the total satellite mass [38]. The added harness mass puts additional constraints on the cost of the mission launch and fuel requirements. Therefore, the space industry is considering novel and out of the box solutions for future small satellite missions.

The European Space Agency, in particular, has initiated projects to implement optical communication for inter as well as intra spacecraft communication [39-40]. As part of the inter-satellite communication activities, the first optical inter-satellite communication link was successfully established between the SPOT-4 and ARTEMIS satellites, proving the concept of utilizing optical communication technologies. In 2006, the Japanese Space Agency (JAXA) demonstrated a bidirectional optical link between its satellite and ARTEMIS. A number of in orbit communication solutions have been demonstrated on-board the spacecrafts in the last few years [10-15]. Although there have been initiatives of light based communication for relatively larger satellites, there has not been much research and development of implementing optical communication for relatively smaller satellites.

A trade-off analysis of wire and wireless communication solutions for small spacecrafts was performed based on the recent literature review [20-27]. The traditional wired approach is least affected by the radio interference, achieves high security and reliability but at the expense of harness complexities.

The wiring harness mass of wired communication systems imposes a drawback to the ever decreasing sized satellites. In order to minimize the harness mass, different wireless solutions including optical and radio frequency (RF) based have been demonstrated in some space missions [20-27]. The use of smart intra-spacecraft data communication using optical and radio frequency is expected to rise in future missions.

The intra spacecraft optical communication has numerous advantages over traditional wired communication mainly in the reduction of harness mass complexities, provision of electrical isolation between multiple connected devices reducing the potential short circuits, reduction of electromagnetic interference in high speed lines, overcoming of bandwidth limitations, overcoming of capacitive effects, skew and propagation delays in high frequency lines [37].

In order to investigate numerous advantages of optical communication over its radio frequency counterpart, an analysis of short range optical and radio frequency based solutions was performed [10][14]. The state of the art in optical and RF technologies is shown in Fig.1 (courtesy [14]). The Bluetooth and the infrared solutions can be effectively used in small satellites when the data rate requirements are not stringent. The choice of innovative communication solutions becomes obvious for future missions where data rate will be one of the driving factors. The use of technologies implementing protocols like 802.11 and GigaIR will become dominant in small satellite platforms for high data rate requirement. In order to provide high data rate serial links using optical data communication, the ECSS standardization on space fiber is in the assessment review phase [36].

The optical communication systems have many advantages over radio frequency communication systems that include immunity to electromagnetic interference, immense unregulated bandwidth, higher data rate and relatively lower power consumption. The RF based intra spacecraft communication is potentially more prone to electromagnetic interference of onboard radio frequency sensors. The infrared optical solution consumes significantly less power than Bluetooth technology. The optical infrared hardware is also less expensive than Bluetooth radio modules, making it a perfect choice for low cost space missions. Although there have been only a few in-orbit demonstrations of the onboard optical solutions so far, they are expected to increase in near future.

With several advantages of optical communication, there are also some drawbacks to be considered. The optical communication is prone to interfere with ambient light requiring many stages of filtering. The self-interference of same wavelength can cause problems in order to implement multichannel communication inside the spacecraft. One solution to this potential drawback is to use multiple wavelengths separated apart to achieve a working link. Furthermore, the optical devices including the glass fibers are prone to effect of radiation dose. Therefore, optical devices need to be tested in radiation environment before being used in the implementation.

Fig.1 Analysis of Radio Frequency based and Optical based communication solutions [14]

There are many commercial transceivers available in the market to provide low cost and low power optical communication solutions but they typically do not qualify the stringent functional requirements in space radiation environment. In space environment, the commercial transceiver's functionality might be compromised due to variations in temperatures over the orbital period and also due to the induced total ionizing dose (TID). Moreover, the commercial transceivers are typically designed not to handle large variations in incoming photocurrents and rejection of selected low frequency noises. Therefore, we propose a discrete transceiver with flexibility in selection of bandwidth, rejection of ambient light, and provision of interfacing radiation tested optical components.

In order to implement the numerous advantages of optical communication inside the small spacecraft, the designed discrete transceiver is used as a demonstrator for free space optical as well as glass fiber based intra spacecraft communication. The implementation has been accomplished on the AraMiS architecture [16-19]. This architecture provides flexible, modular and scalable small satellite bus which can be sized according to the payload demands [1-3],[4-9]. The architecture gives flexibility at each design level i.e. module, panel and satellite. The subsystem can be designed on small modules, which in turn are integrated into a flexible panel called tile. These panels or tiles are sized and assembled in any desired satellite configuration.

The paper follows the following sequence. Section 2 describes the module design and implementation, section 3 discusses the radiation test analysis of selected optical components and section 4 details the intra satellite communication architecture using free space and glass fiber based solutions.

2. Module Design

In the initial phase, the requirement analysis of optical module was performed which consisted of data rate and placement requirements. The typical requirements for intra spacecraft data communication are low baud rate (0.5~1Mbps) and short distance [30]. For short range transmission purposes, the vertical-cavity surface-emitting laser (VCSEL) and light emitting diodes (LED) are commonly used in infrared wavelength range (850nm or 1550nm). The implementation of the transceiver is based on discrete devices as opposed to the commercial option to ensure functionality in space environment. The discrete option provides flexibility in the selection of optical components in terms of technology and wavelength.

The working prototype of the module was designed consisting of transmitters and receiver blocks with several amplification and filtering stages. The transceiver module to handle a high dynamic ranges of signal currents was designed to handle signal currents as small as few nA up to fraction of mA . In the implemented transmitter as shown in Fig. 2(a), the radiated optical power (P_o) is directly proportional to the amount of current flowing through LED (I_{LED}) given by (1).

$$P_o = k \cdot I_{LED} \quad (1)$$

Where k is the optical efficiency of the LED. The amount of current flowing through LED is controlled by appropriate resistance (R_D) computed by (2).

$$R_D = \frac{V_{CC} - V_F}{I_F} \quad (2)$$

Where V_F (1.3V – 2V) and I_F are the forward voltage and the resultant current flowing through the light emitting diode. Some commercially available LEDs and photodiodes were tested and evaluated for the designed transceiver [12-14]. The transmitter can generate a range of radiant intensities based on the available power. The module has been designed to operate in any form factor of typical nano and microsatellites.

The photodiode current can be monitored by direct voltage monitoring or current to voltage conversion. In direct voltage monitoring, the diode current is supplied directly to the resistive load. The implementation of this technique is quite simple but it has many limitations. The main limitations are severe bandwidth degradations, non-linearity and dc offsets in the received signals. In current to voltage conversion technique, the diode current is converted to corresponding voltage by the use of trans

impedance amplifier (TIA). Owing to the advantages of current to voltage technique over direct voltage monitoring, it has been used in the implementation.

The most challenging part in the design of transceiver is to handle large variations in the received photocurrents. Since a receiver can receive more photocurrent in direct line of sight and exceptionally less at a certain angle w.r.t. transmitter, the variation in the received photocurrent is from few nA to fraction of mA range. Therefore, the transceiver should efficiently handle a very broad dynamic range. In order to accomplish it, the receiver was designed in two stages; the first one with relatively lower gain to handle variations in received photocurrent and the second one with the desired voltage gain. In order to filter out the ambient light and low frequency noise, the second stage amplifier also acts as a high pass filter [36]. The corresponding transmitter and receiver stages of the designed transceiver are shown in Fig.2 (b). The gain expression of the first stage is given by equation (3) which is dependent on the feedback resistor (R_{f1}). The component values are chosen such that the gain is lower to handle potential variations in the photocurrents.

$$H_1(s) = -\frac{V_{out1}}{I_{in}} = -\frac{R_{f1}}{1+R_{f1}C_1s} \quad (3)$$

Fig. 2 Transceiver Block Diagram (a) Transmitter (b) Receiver

The gain expression for the 2nd stage is expressed in (4).

$$H_2(s) = -\frac{V_{out2}}{V_{out1}} = -\left(\frac{1}{1+R_{f2}C_2s}\right)\left(\frac{R_{f2}C_{z1}s}{1+R_{z1}C_{z1}s}\right) \quad (4)$$

Fig. 3 Frequency response of 1st and 2nd stage

The frequency response of 1st and 2nd stage is shown in Fig.3. Since the 2nd stage is designed to filter out the ambient light, therefore it has a band pass response with the first pole at relatively low frequency (300 Hz). The 2nd stage voltage gain is sufficiently higher than the 1st stage gain (26dB higher in Fig.3). The expression for -3dB bandwidth for the 1st and 2nd stages is given by (5).

$$f_{-3dB} = \sqrt{\frac{GBWP}{2\pi R_{fn} C_{IN}}} \quad (5)$$

The gain bandwidth product (GBWP) is fixed for chosen op amp whereas discrete values of resistor and capacitor combination help in selection of desired bandwidth. In case of implemented transceiver, the Fig.3 shows that the -3dB bandwidth is 10MHz whereas our signal of interest is 1MHz with 20% duty cycle.

A dynamic threshold comparator was designed as a 3rd stage considering the fact that the incoming pulses have unpredictable behavior of received photocurrents [36]. The designed comparator performs the comparison between output of 2nd stage (V_{out2}) and its average value. The equation (6) gives the expression for time constant of the designed threshold comparator.

$$\tau_{T1} = (R_{T1} || R_{O1}) \cdot C_{T1} \quad (6)$$

The offset voltage (V_{off}) is a positive small value (at least 50mV) which can be selected by use of (7) and (8).

$$V_{off} = V_{CC} \frac{R_{T1}}{R_{O1} + R_{T1}} \quad (7)$$

$$\frac{R_{O1}}{R_{T1}} \leq \frac{V_{CC}}{V_{off}} - 1 \quad (8)$$

The selection of resistor ratio in the threshold comparator has to comply with the above expression for proper functionality.

Fig. 4 Simulation results of transceiver stages

The output voltage level after the amplification stages and the threshold comparison stages is shown in Fig.4. The module was tested for the complete dynamic range of the received photocurrents by varying the distance between transmitters and receivers and the results are plotted in Fig. 5. The graphs suggest that in a form factor of small satellite, the transceiver can effectively handle a range of radiant intensities.

Fig. 5 Received photodiode current at selected separation between transmitter and receiver

3. Radiation Analysis of Optical Components:

The total ionization dose (TID) of 10krad is estimated for mission life time of five years. This estimation is based on the thickness of mechanical structure, the orbital parameters and orbit type for each panel body [34-35]. For the estimation, low earth orbit with 800Km altitude was selected (data calculated using OMERE [22]). The optical components [31-33] are more prone to space radiation effects; therefore, their testing is necessary before use. The optical components mostly suffer from the displacement damage effect [28-29] and the device tolerance to this damage can be tested by exposing it to the radiation source with and without bias and measuring the performance. The components were evaluated with various

radiation exposure levels and the results depicting the LED output power and photo-diode sensitivity are plotted in Fig. 5.

Fig. 6 Plot of LED radiant intensity and Photodiode sensitivity for certain angular displacement at various TID levels

The percentage decrease after the exposure of radiation dose of 10 times the mission life is plotted in Fig.6. It can be noticed from the results of various tests on optical components that LEDs undergo less than 15% attenuation and the selected photodiodes undergo less than 7% attenuation when irradiated with a TID ten times the specific mission. The radiation test analysis suggests that any of these optical components can be used because the degradation remains within the allowable limits. Another critical analysis is the displacement damage on the optical components which will be carried out in the next design stages.

4. Implementation:

The total ionization dose testing on selected optical components is promising in the utilization of these devices in space environment. The main objective of this section is to propose certain schemes where the prototyped transceiver can be used to show the potential of intra-satellite optical communication. We propose both free space optical links as well as glass fiber optical links for intra spacecraft data communication. The theoretical calculations and experimental results for free space optical intra satellite

link as well as glass fiber based link are described in detail to validate the use of optics inside the spacecraft as a communication medium.

The radiation pattern graph of [31] is given in Fig. 7 with relative intensities at certain angular positions illustrated. This is specifically helpful in critical angle selections for glass fiber based implementation.

Fig.7 Relative intensity of Vishay [31]

4.1 Free Space Optical Implementation

The discrete optical infrared transmitters and receivers were tested for different free space link distances. The radiation intensity i.e. radiated power per unit solid angle, at a distance r from the source of optical power, is given by (9)

$$I_{received} = \frac{P_{inc}}{r^2} * A_{Photo} * Responsivity \quad (9)$$

Where P_{inc} is the incident optical power on the receiver, and A_{photo} is the effective area of the photodiode. One of the proposed schemes for inter panel free space communication is shown in Fig.8. It considers the placement of transmitters and receivers in the most optimum places to achieve a working link. The transmitters 1 and 2 can use either the same wavelength or different wavelengths to avoid interference in the reception. The reception results at top, center and bottom corners by turning on both the transmitters separately are plotted in Fig.8. The theoretical received current (using eq.9) and the practical received current (using experimental setup) closely match with each other thereby validating the proposed transceiver design. Due to a wider field of view, the center receivers can also receive the signals of transmitters 1 or 2. All of these received photocurrents are effectively handled by the designed transceiver.

(a) Free space demonstration (b) Plot of theoretical and practical results

The theoretical and experimental results suggest that for panel based small spacecrafts, this type of wireless configuration can be used for inter panel communication. For the traditional spacecrafts with avionic boards mounted in the middle racks, this type of configuration can be challenging since maintaining the optical wireless link across different avionic boards is not possible. The optical light guides can be used to interconnect the panels in these types of spacecrafts.

4.2 Glass Fiber Based Optical Implementation

A number of glass fiber based configurations for reliable inter panel communication were studied and one of the proposed implementations is shown in the Fig 10. *Plexiglass* or *polymethyl methacrylate* was used for initial idea testing since this was the only available option for demonstration in laboratory conditions. In order to guide maximum radiant intensity to the glass fiber, we use Snell,s law which is given by (10).

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_1}{n_2} \quad (10)$$

Where θ_i and θ_r are the angles of incidence and reflectance respectively. The angles are measured from the normal to the surface, at the point of contact, as shown in Fig. 9. The n_1 and n_2 are the indices of refraction for air and glass.

Fig.9 Optical light guidance in the fiber

The angle of incidence of light that make sure that all the optical light is guided inside the glass fibre is given by (11).

$$\theta_i = \sin^{-1} \frac{1}{n_2} \quad (11)$$

This expression gives critical angle for which the incident ray does not leave the glass fibre, namely when the angle of reflectance is 90° . Therefore using equation (11), we guarantee that the total internal reflection (TIR) takes place at a critical angle of approximately 41° .

For the implementation of glass fiber based configuration for a cubic configuration, the proposed model is shown in Fig.10.(b) The double reflected mirrors are placed to pass the part of light straight through and part of it at particular angles as shown in Fig. 10.(a). In this configuration, we utilize the internal sides of the lateral satellite panels for light guides as shown in Fig. 10(a). For each panel, the light guides have been placed in an identical way with beam splitters and transceivers. Once the panels are connected together in a cubic configuration, each panel has possibility to communicate with the other one as shown in Fig. 10(b). Due to the placement of transceivers at known positions on each panel, we can accomplish the communication along all connected panels using proposed scheme.

The light intensity is guided in the system in such a manner that the photocurrent received by a node closer to the transmit node and that received by a node far from the transmit node don't saturate the receivers. The receiver doesn't saturate since it has high dynamic range and is able to process the photocurrents of the specified range.

Fig.10 (a) Architecture of glass fiber based communication showing panels (b) Proposed model for guided optical light for cubic structure.

The responsivity of the photodiodes is dependent on the wavelength and so is the received current. The received current ($I_{received}$) depends on the incident power (P_{inc}), active area of the photodiode (A_{photo}) and effective diameter of the light guide (ϕ). Its theoretical can be expressed as given by (12).

$$I_{received} = \frac{P_{inc}}{\frac{\pi}{4} * \phi^2} * A_{photo} * Responsivity \quad (12)$$

Fig.11 shows the photograph of light guide, results of theoretical and received current waveforms and experimental setup for the experiment.

Fig. 11 Photograph showing (a) guided light propagation. (b) Experimental setup for receive current measurement (c) Receive current for up to two stages

The theoretical and measured values of received current for different values of input radiated optical power are depicted in Table I. The theoretical results are calculated for *plexiglass* of $\phi = 7.5mm$ and using [31] with photodiode of $4mm^2$ active area.

The preliminary results were obtained taking into account the communication in a single light guide and using a stage of beam splitters for two light guides. For low data rate requirements, the commercial optical protocol (IrDA) requires BER lower than 10^{-8} for the long packet format i.e. the packet length of 256 bytes or more. The results using a single light guide suggest that the achievable BER is lower than 10^{-12} that is well inside the limits. However, the results of connecting more light guides increases the error rate. One solution to minimize the BER to acceptable level for multiple guides is to use re transmissions. Since the preliminary results are taken to validate the idea of using optics inside the spacecraft, further consideration has yet to be made for unaccounted losses e.g. losses at the beam splitter junctions, losses

due to signal reflections, ambient light and misalignment losses due to interface of transmitters and receivers with the light guide. The next step in the design is to minimize the BER to an acceptable value for the configurations that use two or more light guides in the cube. It will be achieved by the use of more compact transceivers, improved design of beam splitters and better interconnections for glass fibres.

5. Conclusion

In this paper, we have shown the design technique of building discrete optical transceiver using COTS components for intra satellite optical communication that provides flexibility in using discretely radiation tested optical components. The designed transceiver is used in free space as well as in glass fiber guided modes to demonstrate intra spacecraft optical communication solutions. The initial results for free space as well as guided light communication illustrate that optical links can be utilized in bigger spacecrafts but they have few limitations for small spacecrafts mainly in ensuring line of sight for free space optical links. The data communication solutions using both free space and fiber based can be used together to reduce the limitation of intra spacecraft optical communication. The proposed optical communication systems will be used along with the other wired communication approaches for more flexibility.

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Table1

No. of Guides	Radiated Power Po(mW)	Responsivity (A/W)	Received current Theoretical (mA)	Received current Measured (mA)	Difference (%)	BER
1	10	0.47	0.42	0.39	7.1	$<1 \times 10^{-12}$
	20	0.47	0.85	0.78	8.2	$<1 \times 10^{-12}$
2	10	0.47	0.21	0.16	23	$<10^{-6}$
	20	0.47	0.43	0.28	34	$<10^{-6}$