Design of Wireless Umbilical for smart swim-out type payloads

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Abstract— Umbilical cables are used to provide power and initial configuration data to payloads pre-launch. Conventional umbilical use customized connectors with snapping or cutting mechanisms inside launcher which suffer from limited reusability, ESD during snap-off, pins damage, no inherent security features and jerky operation. A wireless umbilical with self-aligning feature has been designed to overcome these problems. A matched impedance, ZVS-on, singles witch Class E amplifier has been designed to feed a set of dual layer composite coils for wireless transfer of 280W power at 6.78MHz. A laser-based hardware running custom software protocol has been designed to achieve robust wireless datalink at 1Mbps bitrate.

Keywords—Wireless power, Class E power amplifier, ZVS, optical communication.

I. Introduction

A typical umbilical cord has subsystems to facilitate power and data transfer from platform to payload pre-launch. Conventional wired umbilical use male-female receptacles with separate pins for data and power transfer. The receptacles are held together by special snap-off mechanisms for drop type weapons or screwed mechanisms with shearing knife edge for powered launch systems. During separation, these mechanical systems are required to operate in high corrosion, high pressure, high stress, high ambient temperatures and high EMI environments which limits usable life and reliability. Replacement of these systems post launch from platform often requires turn-around of platform to maintenance affecting valuable operational time. To alleviate these problems, a self-aligning, inherently secure umbilical which has forward compatibility with smart weapons has been designed with a small footprint. This umbilical is based on wireless power transfer at 6.78MHz (upto 300W) with free space optical communication (FSOC) link up to 1Mbps speed.

II. SYSTEM DESIGN

System design has been divided into 05 sub-assembly design problems based on requirements viz. (1) Design of Wireless power transfer coils (2) Design of Power circuit and resonant tank (3) Design of Free Space Optical Communication (FSOC) system @ 1Mbps bit rate (4) ATEX analysis of design and incorporating changes (5) Housing and auto-alignment mechanisms. Three parts of this design are presented in detail in this paper.

A. *Design of Wireless power transfer coils*

The initial point of coil design is to determine the system requirements and operating conditions of coils. The max continuous current carrying capacity of coils is 16A @ 28VDC (designed as per IPC2221A for 4mm track width, 70µm height and allowable rise of temperature 40̊C above ambient), outer diameter (Dout) = 75mm(preferably), innerdiameter(D_{in})=14mm(mintoaccommodatelaserandphoto diode), operating frequency is 6.78MHz(AirFuel resonant standard),max allowed ΔV between tracks 150V,capable of operating at >3000m ceiling continuously with surface temperature not exceeding 135̊Catany point and compatible with MIL810H operating conditions.

The substrate material is Rogers RO4350B LoPro 0.536mm upon which tracks are to be manufactured as dielectric constant of the material is low (3.48) and minimizes RF losses. The spiral factor(a) of an Archimedean spiral is given by a=pitch/2π.Thepitchof the designed coil is 5mm (4mm effective track width + 0.2 mm between strands + 0.6mm between turns). Hence, spiral factor a = 0.795774 rad/mm. Next, we need to estimate DC and AC resistances of the coils to compute efficiency and assess the coil's performance. The DC resistance (RDC) and AC resistance (RAC) of a planar spiral are given by expressions below:

$$R_{dc} = \frac{l}{\sigma \omega h}; R_{ac} = R_{dc}\left(\frac{h}{d\left(1 - e^{\frac{-h}{d}}\right)}\right) \quad (1)$$

Where
σ = 5.96x107 S/m for copper,
ω = 4mm (track width),
h = 70µm (trace thickness),

$$l = \pi N \frac{\left(D_{out} + D_{in}\right)}{2}$$

D_{out}= 80mm, D_{in} = 15mm, No. of turns N = 5 implies, l = 746.13mm. Substituting in (2) we get RDC = 0.0447Ω. In (2) for RAC, d_{cu} is skin depth at 6.78MHz for copper which is given in (3) as evaluated by Gyimothy et al. [4]:

$$d_{cu} = \begin{cases} \frac{66}{\sqrt{f_{sw}}}, & T = 25^{\circ} C \\ \frac{76}{\sqrt{f_{sw}}}, & T = 100^{\circ} C \end{cases} \quad (2)$$

Considering T = 25°C, and f_{sw} = 6.78MHz, we get skin depth of copper as d_{cu} = 0.025347mm = 25.347µm. Substituting d_{cu}, h = 70µm and R_{dc} = 0.0447Ω in (2), we get R_{ac} = 2.948Ω for the designed coil at 6.78MHz.

The next step is to estimate self - inductance of the spiral which is given by Wheeler's formula for planar spiral as:

$$Lcoil = \frac{\mu_0 N^2 D_{avg}}{2}\left[\ln\frac{2.46}{\beta} + 0.20\beta^2\right] \quad (3)$$

Where,

Permeability of free space $\mu_0 = 4\pi 10^{-7}\ H/m$

N is number of turns = 5,
Copper fill factor is

$$\beta = \frac{D_{out} - D_{in}}{D_{out} + D_{in}} = 0.6842$$

$$D_{avg} = \frac{D_{out} + D_{in}}{2} = 47.5mm$$

Substituting in (3) we get

$$L_{Coil} = 1.0246\mu H$$

A set of wireless power transfer coils can be modelled as a loosely coupled transformer with air core and larger distance between the primary and secondary windings. Loosely coupled windings imply higher magnetic flux leakage which translates to higher reactive power in system, higher energy loss and lower transmission efficiency (η_{TR}). To boost η_{TR} of the coil set compensatory capacitors are introduced on both Transmitter (T_x) and Receiver (R_x) sides. Fu et al. [5] analyzed various compensation topologies, evaluated expressions for ηTR in each case and presented expressions for reflected load resistance in each case to indicate dependency on various system parameters. It is observed that Series-Series (SS) compensation has advantages in terms of ease of analysis and design, reflected load resistance (R_r) being independent of leakage inductance of coils, value of compensation capacitors independent of Rr and zero reflected reactance (X_r) when natural frequency equals switching frequency f_{sw}. The evaluated expressions for primary and secondary capacitors in SS configuration are

$$C_{S1} = \frac{1}{\omega^2 L_{lp}}, C_{S2} = \frac{1}{\omega^2 L_{ls}} \quad (4)$$

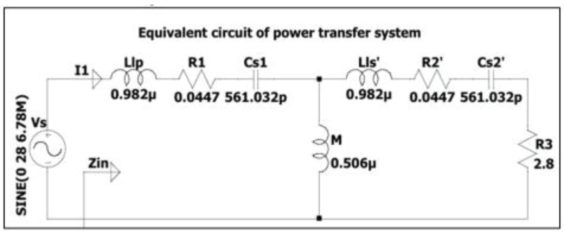


Fig 1. Equivalent circuit of wireless coils

The transmission efficiency expression when evaluated and simplified is similar to as evaluated by Fu et al. [5] for SS compensated topology and is given as:

$$\eta_{TR} = \frac{P_{out}}{I_1^2 Z_{in}} = \frac{\omega_2 M_2 R_L}{[R_2 + R_L][\omega_2 M_2 + R_1(R_2 + R_L)]} \quad (5)$$

Where M is the mutual inductance and ω is the frequency. It can be observed that the transmission efficiency η_{TR} is dependent on coupling, load resistance, coil resistances and operating frequency of the system. This is used to optimize the coil design in ANSYS and power circuit in MATLAB/Simscape. Safaee. A et al. [6] introduced a parameter called "Strong coupling coefficient" in time domain analysis of SS compensated inductive power transfer circuit. The same can be adapted to resonant power transfer circuit by replacing ω with ω_r and simplifying further. The quality factor *(Q)* and coupling factor *(k)* of a magnetically coupled circuit can be written as:

$$\eta_{TR} = \frac{Q_1 Q_2 K^2}{\left(1 + \frac{R_1}{R_2} + Q_1 Q_2 K^2\right)\left(1 + \frac{R_2}{R_L}\right)} \quad (6)$$

The term $(Q_1 Q_2 k^2)$ is defined as the strong coupling coefficient where in the weak coupling arising out of a large distance between coils is compensated by high Q value coils. This essentially makes a case for resonant magnetic coupling wherein the Q of the coils is usually very high >1000 as compared to that of inductive coupling in which it is in order of 100s at the most. The problem is then optimization of this strong coupling factor. This has become the basis for choosing the configuration and opting for magnetic resonance mode of wireless power transfer in this paper.

The chosen operating frequency for achieving resonant wireless umbilical is 6.78MHz Air Fuel Resonant standard (ISM band). This enables miniaturization of circuit components and usage of commercially available shields and filters. However, this high switching frequency induces problems such as high skin (25um depth as calculated in (2)) and proximity effects which increases RAC and losses thereon. Several studies [7-14] have been done to evolve a pattern of planar coils in which these effects are reduced. Two patterns in particular have promising results in combating AC losses, a reduced solid track width PCB coil and Litz pattern style PCB coil [7]. When track width of a solid track coil is reduced, the gap between subsequent spiral arms increases thereby reducing the self-linking leakage flux and proximity effect. However, reducing track width increases RDC and increases Tsurface which is not desirable. Therefore, two PCB patterns viz. Fully transposed layers pattern and Partial transposed layers (Litz[16]) have been e v o l v e d i n this paper. The coils were optimized and evaluated in ANSYS Maxwell 3D. Each coil consists of two layers (top and bottom). Each track on a layer consists of 02 nos of 2mm wide parallel strands separated by 0.2mm gap. Adjacent spiral tracks are separated by a 0.4mm gap. The thickness of copper deposit used is 70μm and its density is 2 oz/ft2 for enhanced overload performance. Each layer has 08 nos of 2mm wide cuts in tracks at 45° intervals which are used for transposing layers through vias[15]. A set of various patterns viz. (a) Solid track, 4mm width, 5 turn, d=20mm, (b) Parallel strands (08 strands), 4mm wide, 5 turns, d= 20mm, (c) Fully transposed dual layer composite (02 strands per layer), 4mm wide, 5 Turns, d= 20mm, and (d) Dual layer Litz pattern composite (02 strands per layer), 4mm wide, 5 Turns, d= 20mm have been constructed and simulated in ANSYS Maxwell 3D to evaluate their performance.

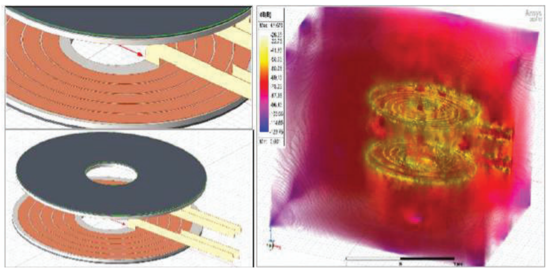


Fig 2. Solid track w =4mm, 5Turns, d= 20mm; B-field pattern

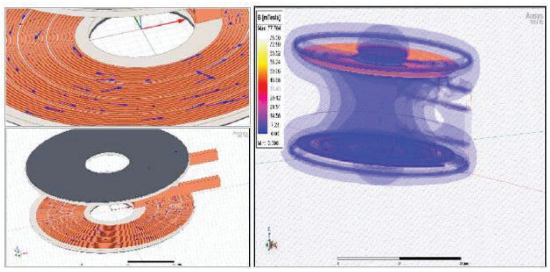


Fig 3. Parallel strand (8 strands 0.5mm wide), 5turns, d = 20m

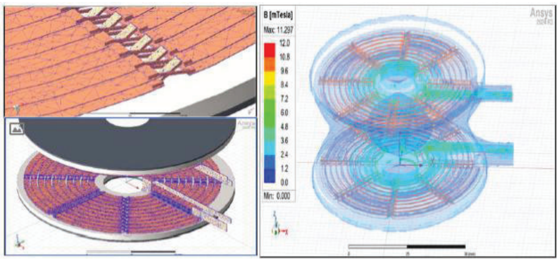


Fig 4. Fully transposed dual layer composite coil

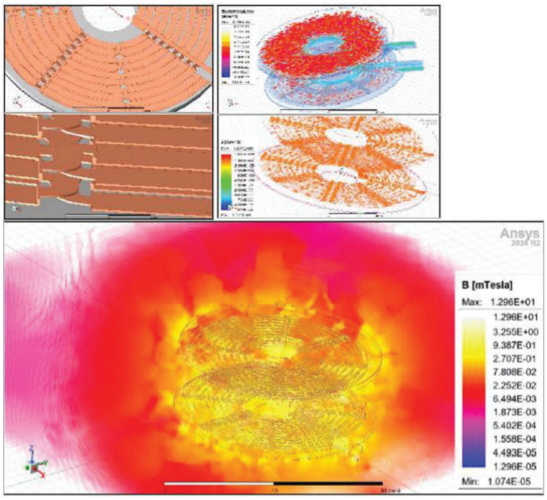


Fig 5. Litz pattern dual layer composite coil set

Results of various parameters obtained for different patterns of 4mm track width, 5Turn, d = 20mm @ 6.78MHz are as tabulated below in ***Table 2***. It can be observed from above results and figures, that a solid track coil is unsuitable owing to high skin effect and consequent failure due to high localized heating.

Parameter	Solid track	Stranded track (8 strands)	Fully Transposed (Dual layer coils)	Litz pattern (Dual layer coils)
Self-inductance (µH)	1.644	1.181	1.627	1.4865
Mutual-inductance (µH)	0.472	0.254	0.456	0.443
Rac (mΩ)	304.6	178	192.36	237.55
Coeff of coupling(k)	0.286	0.215	0.2803	0.2971
Solid loss(W)	57.17	23.126	13.2	14.87
Bmax (mT)	47.7	72.8	12	13

Table 2. Parameters of various pattern coils from ANSYS

The stranded track seems to have performed better but the inner tracks carry almost zero current. This will lead to a catastrophic heating and eventual failure of the coil. Dual layer, twin track coils perform better owing to transposition and reduction in proximity effects. Litz pattern has better performance metrics amongst two patterns (near zero proximity effect) and is the preferred choice in this design despite having higher Rac. Further, the ac to dc resistance ratio in Litz pattern is constant over a wide switching frequency range.

Sno	D(mm)	L_{coil}(µH)	k(coupling)	L'_{lp}, L_{ls}'(µH)	C'_{s1}, C'_{s2}(pF)	L_p (nH)	C_p (nF)
1	16	1.5015	0.3833	0.9229	596.91	46.80	11.774
2	18	1.4970	0.3407	0.9820	561.032	43.988	12.527
3	20	1.4865	0.2980	1.0435	527.953	41.395	13.3117
4	22	1.4789	0.2484	1.1115	495.64	36.861	14.18
5	24	1.4763	0.2247	1.1446	481.34	37.74	14.6
6	25	1.4753	0.2112	1.1637	473.4	37.12	14.8447

Table 1. Various circuit parameters for various values of d from ANSYS

With a Litz pattern coil set, a parametric sweep by varying d from 14 mm to 25mm has been performed and coil parameters were recorded. Results in fig 7 and in Table 2.

Exact equivalent circuit with parameter values of Litz pattern coil derived from ANSYS is at Fig 6.

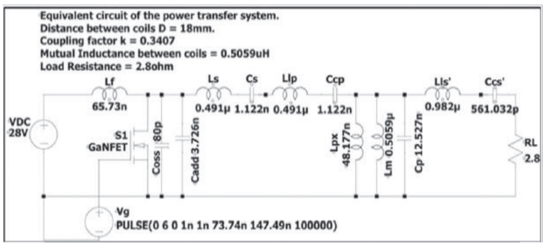


Fig 6. Exact equivalent circuit for Litz pattern coil set

A twin tracked 4mm effective width, 5 turn, dual layer litz pattern coil with Dout = 74.54mm, Din = 15.8mm, 70µm thick copper layer with 2oz/ft2 density with d = 18 has been chosen for hardware realization. The thickness of payload skin is 12mm and considering coil mounting gap of 3mm on either side of quartz window on payload and umbilical housing, d = 18mm is the realistic distance between coils for designed application.

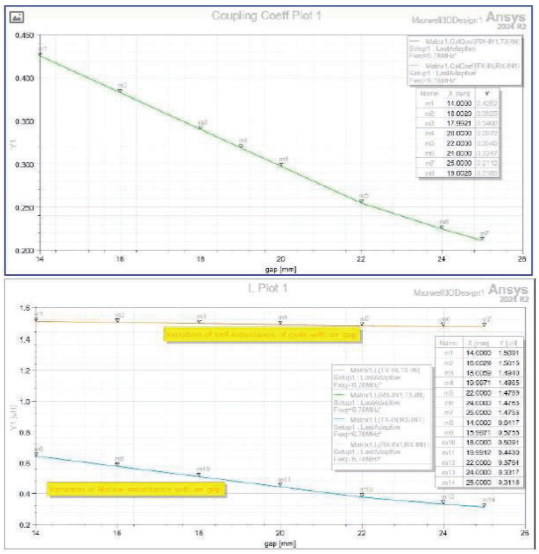


Fig 7. Variation of L_{coil} and k with d for Litz pattern -ANSYS

B. *Design of power amplifier and resonant tank*

L. Roslaniec et al. [3] proposed a rapid synthesis method for determining values of circuit parameters of a single switch Class E resonant power amplifier [1][2] for driving wireless power transfer coils. A similar method has been adopted to calculate the circuit parameters in this design at 6.78Mhz, 30V DC input to transfer 280W of power. GaN HEMT[17] has been used for switch, duty cycle(D) is fixed at 50% with open loop operation. A full bridge Schottky diode is employed at the rectifier end for max speed of operation. The load is assumed to be purely resistive. The output low pass filter is designed to filter out 13.56Mhz ripple components. The input filter is designed to allow for stable ZVS operation for a load modulation of 1:10 (2.8Ω - 28Ω). Considering d = 18mm and plugging in the value of parameters obtained from ANSYS we get an equivalent circuit as shown in figure 13. The description of parameters are as follows: (1) Lf - Input filter inductance (2) Cf - Input filter capacitance (3) Ls - Series inductance of resonant tank (4) Cs - Series capacitance of the resonant tank (5) Lp - Parallel Inductance of the resonant tank (6) Cp - Parallel Capacitance of the resonant tank (7) Llp - Self leakage inductance of composite coil Transmitter (8) Ccp-Series compensation capacitor of composite coil Transmitter (9) Lls' – Self leakage inductance of composite coil Receiver referred to primary (10)Ccs' – Series compensation capacitor of composite coil Receiver referred to primary (11) Lpx – Additional parallel resonant inductance in parallel with primary coil considering mutual inductance Lm of the coils at various distances.

(12) Cadd – Additional capacitor in parallel to GaN switch for input filter Cf. (13) Csnub – Snubber capacitance for switch protection (14) Lcoil – Actual self-inductance of each coil. For sake of prudence, the resonant coils and other resonant tank components have been designed such that self and mutual inductances of these coils become part of the resonant tank.This reduces design complexity and the number of passive components to be placed on PCB. The transmitter and receiver coils have been designed to be identical to each other (Turns ratio 1:1) further simplifying the equivalent circuit (Fig 6.). The simplifying equations are as follows:

$$L'_{lp} = \left(L_s + L_{lp}\right); L'_{ls} = L'_{ls}; C'_{S1} = \left(C_s + C_{Cp}\right); C'_{S2} = C'_{CS} \quad (7)$$

$$L_p = \frac{L_m L_{px}}{L_m + L_{px}}; C_p = C_p; C_f = \left(C_{0SS} + C_{snub} + C_{add}\right) \quad (8)$$

$$L'_{lp} = L'_{ls} = \left(1-k\right) L_{Coil} \text{ and } L_m = kL_{Coil} \quad (9)$$

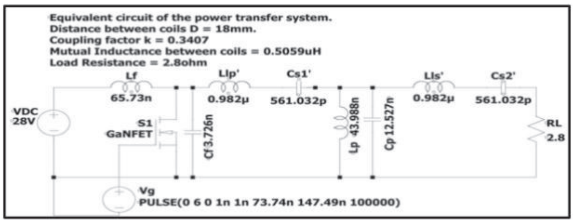


Fig 8. Simplified equivalent power circuit

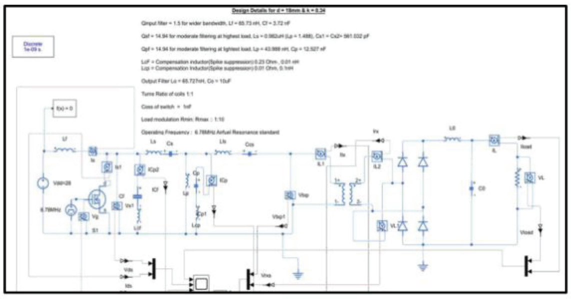


Fig 9. Simscape simulation of power circuit with Litz coil eq. circuit

An output low pass filter is designed for use at load end to minimize ripple content in output voltage and current.The values of output filter can be calculated by expressing outputimpedance(Z_0) in terms of output quality factor Q_0 as

$$Z0 = \frac{RLQ_0^2\left(Q_0^2+1\right)}{Q_0^2+1}$$

The value of Z0 = RL when Q0 = 1. At max loadi.e. R_L = 2.8Ω, L_0 = 65.73µH and C_0 = 8.38nF. Simulation results of the equivalent circuit in Simscape/MATLAB are presented in Figs 10-12 below. Performance of the circuit in terms of maintaining desired output voltage V_0 = 28VDC with variation of load and an additional DC filter capacitor of 10µF have been plotted as shown in Fig 13 below.

It has been observed from the above simulation results that at desired load current of 10A, the output voltage is 28.1V DC (Fig10). The drain to source voltage of GaN peaks at 136V and the switch current peaks at 36A (Fig 11). ZVS turn-on for switch is achieved over a wide load range from 2.8Ω to 28Ω. The coil voltage peaks at 137V. The coil excitation current is a pure sinusoid with 15.2A peak at 10A load (Fig 12).The peak values of current through filter capacitors C_f (Input filter) and C_p (resonant tank) are 27.53A and 27.5A respectively (Fig 12).

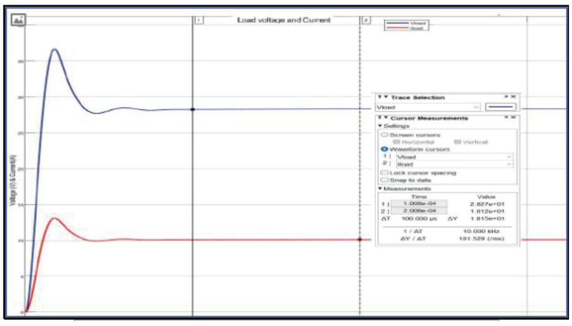


Fig 10. Load voltage and Current waveforms

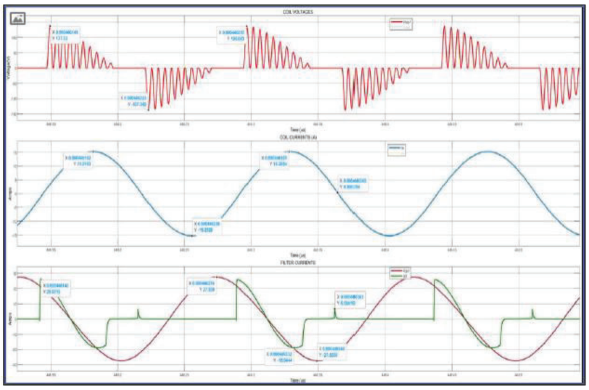


Fig 11. Gate signal, Switch V & I , source current waveforms

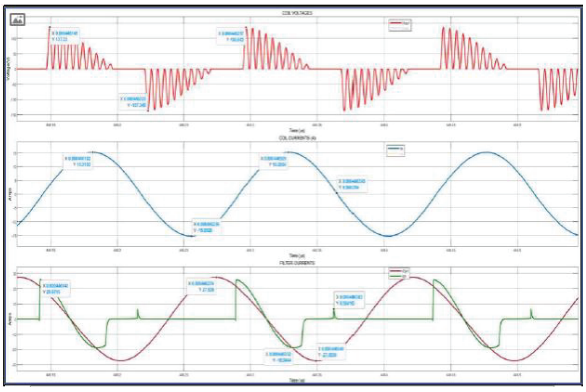


Fig 12. Coil V & I, Filter capacitor currents waveforms

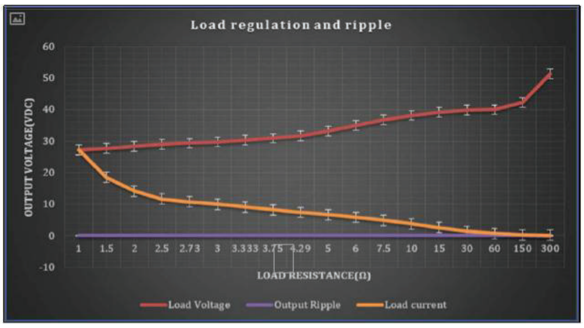


Fig 13. Variation of output voltage with load(1:10) modulatin

C. *Design of FSOC link and Software layer @ 1Mbps*

A simple free space optical communication scheme has been evolved using 520nm visible green laser and photo diode sets on either side. The designed data link is unaffected by a high EMI environment, is inherently secure as it is not powered until umbilical is paired, is EM compatible and is inexpensive.

The hardware layout of the scheme is as shown in Fig 14. A full dual channel optical communication scheme has been designed.The hardware layer consists of a microcontroller which acts as Universal Asynchronous Transmit Receive (UART) controller followed by a Laser driver feeding a laser diode in On-Off-Keying Scheme. The received laser optical signals are received by a wide band photo diode which feeds a Trans-Impedance Amplifier (TIA). The resultant waveform is cleaned by an inverting Schmitt trigger buffer to be fed to the receiving end microcontroller for decoding and response generation. Waveforms are presented in Fig 15 below.

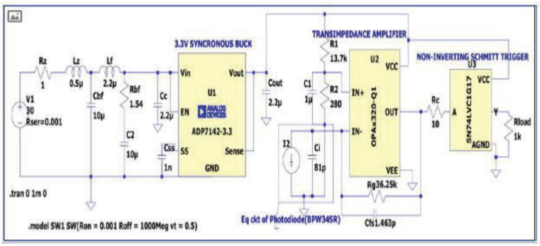


Fig 14. 3.3VDC, TIA (560kHz bandwidth) and Schmitt buffer circuit for 1Mbps

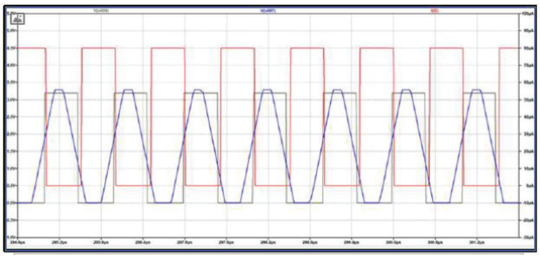


Fig 15. Output waveforms of TIA + Schmitt trigger circuit

Additionally, a 6VDC regulated power supply for GaN HEMT driver, 3.3VDC for microcontrollers and 5.5VDC for oscillators, driver circuits, Op-Amps and buffers have been designed to be operated from 30VDC common rail of the power circuit itself.

The software layer of the communication system is a custom protocol developed for this purpose. The protocol is called FUSFP v1.0(FSO-UART- Secure Framing Protocol). The data frame consists of a preamble word (04bytes) to enable the receiver to lock on to the signal timing before data starts, a sync word(02 bytes) marking start of the frame, a frame word(1byte) indicating the type of frame such as DATA, ACK, NACK, STATLINK , a sequence number (1 byte) which increments every time a new frame is transmitted, a data length byte indicating number of bytes in data payload, the actual data dump to be transmitted, Link Quality Counters(04 bytes) which are simple running tallies indicating data link quality, a 16 bit Cyclic Redundancy Counter(CRC-16) which is a formula based check to confirm accuracy of the data received and a Cipher based Message Authentication code(08 Bytes) to verify the authenticity of the data and to prevent accidental startup of weapon sequence due to noisy ambient light or attempts to sabotage the weapon by shining a laser over the photo receiver. A new set of Transmission and Reception rules have been written based on the above frame structure which cannot be elaborated due to proprietary reasons. The developed FUSFPv1.0 protocol has key advantages in terms of being a self-synchronizing system, strong error detection and correction system, ability to read and display link quality and status to user, is a light weight system which can be run on small microcontrollers like ESP32C3, prevents accidental initiation or sabotage attempts through CMAC authentication protocol and simple framing for debug over widely available UART tools.An example frame is presented in Table 3 below. The overall scheme of implementation of hardware layer is shown in Fig 17.

Sno	FRAME	Frame details
1	55 55 55 55 D5 A7 01 0A 05	Preamble: 55 55 55 55; Sync: D5 A7; Data: 01 Sequence: 0A; Length: 05 (5 bytes payload).
2	48 65 6C 6C 6F 21 00 01	Payload: 48 65 6C 6C 6F ("Hello"); Link counters: 21 00 (33 errors), 01 00 (1 total frame)
3	00 05 00 32 1F A6	CRC-16 (Cyclic redundancy check)

Table 3. Example hex dump frame of FUSFPv1.0 protocol

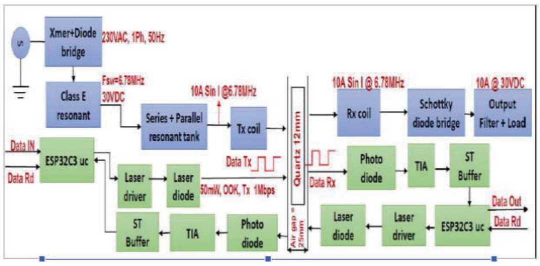


Fig17. Scheme for hardware layer implementation

D. *ATEX analysis and conformal design changes*

The wireless umbilical described in this document is intended for use in explosive environments. Therefore, the designed hardware is required to be in conformance with various MIL and ATEX [18] standards. The product is expected to withstand operating temperatures, thermal shocks, continuous mechanical vibration and shocks, capable of operation in ATEX, high altitude, high EMI and marine environments. Several design features have been incorporated ranging from choice of materials to protective coatings to choosing scheme of operation so that the end product is in compliance with critical requirements of these standards. A factor analysis matrix (Fig 18) has been drawn to arrive at various design choices.

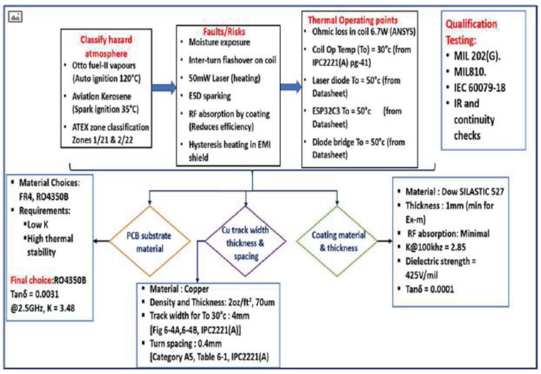
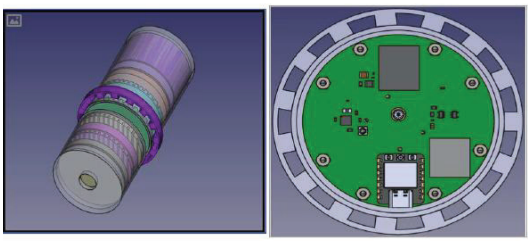


Fig18. Factor analysis and choice of design elements to mitigate risk s identified.

The final product is targeted to achieve ATEX Group-II, Gb, Gc (zone1, zone 2), Db, Dc, T4 class of equipment with Ex-m class of protection. The entire product is enclosed in a dust proof ABS enclosure with quartz glass at open end of the transmission coil. The individual PCBs except that of coils are enclosed in full metal aluminum shielding which are then connected to ground. This ensures compatibility with MIL461F RE102 and CS114 requirements. Further protection by encapsulation is done by coating the wireless coils with 1mm thick DOW SYLGARD SYLASTIC 527 owing to its very high RF transparency, low dielectric loss, ability to protect from shock, chemicals, moisture and dust, has excellent reparability and preventing sparks that emanate from the PCB in even of fault or total failure. Further, all components chosen are D-PAK configuration or auto grade to have compatibility with MIL810H vibrations and shock and also have excellent thermal performance. Cooling is provided by space grade aluminum heat sinks 5mm thick attached to each PCB.

The laser used is 50mW which doesn't cause atmospheric heating thereby eliminating risk of ignition. The choice of communication scheme is FSOC which is totally immune to external EMI and also doesn't generate EMI noise by itself. Alignment of the system is achieved through a series of peripherally placed magnets in the form of a ring around the umbilical periphery to minimize mis-alignments. 3-D drawings of the designed product generated for hardwarerealization are as shown in Figs 19-23.



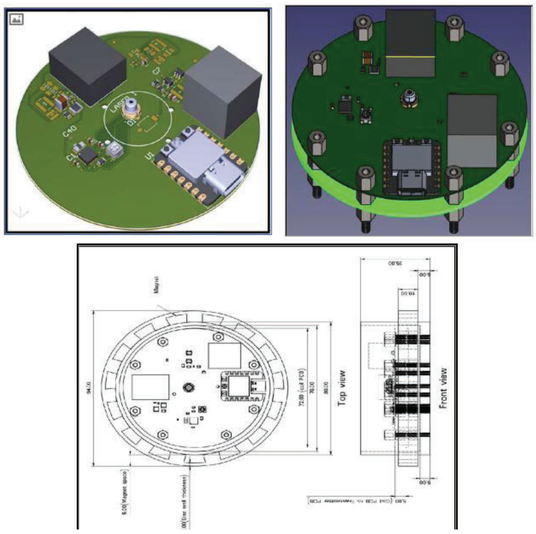


Fig 19-23. Designed Hardware components for prototype manufacturing

III. CONCLUSIONS

In efforts to resolve the problem statement a 6.78MHz wireless resonant power and fully duplex data transfer system has been designed. The novelty of the solution lies in evolving the design of a set of unique dual layer composite coils and robust free space optical communication system with underlying customised software layer which is completely immune to external EMI. The coil parameters themselves have been made part of the resonant tank thereby minimizing the footprint of PCB (Dout = 76mm). A custom FUSFPv1.0 protocol has been evolved to ensure robust data link using lasers over short distances. A self-aligning mechanism using neodymium magnets has been designed to minimise misalignments during mating. Design changes such as specialised conformal coating, using planar PCB instead of Litz wire for coils, choosing materials for higher performance demands have been incorporated in design stage itself to ensure that prototypes are ready for MIL 461F[19], 810H[20], 202G[21] and ATEX/IEC60079 testing. Hardware prototypes are under manufacturing and testing is likely to commence soon.

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