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Radiation-tolerant, low-mass, high bandwidth, flexible printed circuit cables for particle physics experiments

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ABSTRACT

The design of meter long flexible printed circuit cables required for low-mass ultra-high speed signal transmission in the high radiation environment of the High Luminosity Large Hadron Collider is described. The design geometry is a differential embedded microstrip with 100 Ω nominal impedance. Minimal mass and maximal radiation hardness are pre-eminent considerations. Several dielectric materials are compared. To reduce mass, a cross hatched ground plane is applied. The long flexible printed circuit cables are characterized in bit error rate tests, attenuation versus frequency, mechanical response to temperature induced stress, and dimensional implications on radiation length. These tests are performed before and after irradiation with 1 MeV neutrons to $2 \times 10^{16}/\text{cm}^2$ and 800 MeV protons to 2×10^{16} 1-MeV neutron equivalent/cm^2. A 1.0 m Kapton cable with cross hatched ground plane, effective bandwidth of 4.976 gigabits per second, 0.0160% of a radiation length, and no detectable radiation-induced mechanical or electrical degradation is obtained.

1. Introduction

Radiation-tolerant, low-mass, high-bandwidth interconnects are needed for use in the innermost tracking detector of the ATLAS Experiment [1] at the Large Hadron Collider during the coming High Luminosity (HL-LHC) era of operation, when the instantaneous luminosity will increase to $10^{35}/\text{cm}^2/\text{s}$ [2] and the experimental environment will pose extreme constraints upon the detector design. The development of these interconnects is described here, with attention to their response to radiation levels beyond 2×10^{16} 1-MeV neutron equivalent/cm^2 for two radiation species.

The tracking detector is likely to include silicon pixel sensors that are bump bonded to readout electronics and mounted on cylindrically symmetric mechanical support structures ("staves"). The cables that are the subject of this paper will transport the differential signal a distance of 1.0 m from the on-detector amplifier electronics to a 6.0 m cable [3] outside the active volume of the experiment.

It is predicted [3] that the on-detector amplifier electronics will produce data at a rate of 5 gigabits per second (Gbps) per chip; thus a high speed cable is needed. The cable will be exposed to levels of radiation up to 1×10^{16} 1-MeV neutron equivalent/cm^2 (1-MeV neq/cm^2) over its lifetime [2], so optical cables will not survive. Its mass is limited to minimize multiple scattering in the active volume. We explore solutions optimized for radiation hardness, high bandwidth, and low-mass by investigating flexible printed circuit ("flex") cables in various dielectric materials including Kapton. Kapton is a polyimide film developed by DuPont [4]. In this paper the terms Kapton and polyimide are used interchangeably.

New results presented here include comparative implementations of different dielectric materials and effects of cross hatched versus solid ground planes. For each material and ground plane configuration, several geometries and designs have been explored. Identical characterization protocols were applied to all cables before and after irradiation with 1 MeV neutrons to $2 \times 10^{16}/\text{cm}^2$ and 800 MeV protons to 2×10^{16} 1-MeV neq/cm^2. The cables are characterized in bit error rate tests, attenuation versus frequency, stress inducing temperature cycling tests, and dimensional implications on radiation length. Prototypes were produced in 0.5 m and 1.0 m lengths. A Spice [5] model was created to extract signal loss parameters from simulations validated with measurements.

2. Designs and geometries

The baseline design is a differential embedded microstrip arrangement produced by QFlex [6], with 50 μm cover layers above the differential signal traces and below the ground plane. The target impedance is 100 Ω achieved with minimum material. Dimensions of several prototypes studied are shown in Table 1. A schematic of the baseline design is shown in Fig. 1. Benefits of this

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Table 1
Dimensions of several flex cable designs investigated, in cross-section. Dielectrics AP and TK are "all-polyimide" [7] and "Teflon–Kapton" [8] composites respectively. Letters A–F refer to features of Fig. 1.

Cable dimensions	0.5 m AP	1.0 m AP	1.0 m TK
Dielectric thickness (A):	118 μm	125 μm	75 μm
Copper thickness (B):	35 μm	18 μm	36 μm
Trace width (C):	200 μm	250 μm	180 μm
Space between traces (D):	584 μm	500 μm	265 μm
Ground plane width (E):	1130 μm	1600 μm	1000 μm
Cover layer thickness (F):	42 μm	50 μm	30 μm

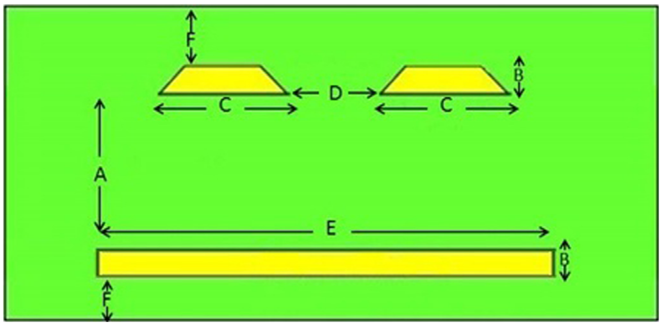

Fig. 1. A schematic cross-section for the baseline design. Labels correspond to Table 1. The difference in width at the upper and lower surface of the signal traces is a natural effect of the etching process. It is exaggerated in this drawing and amounts to a difference of 12.5 μm in the manufactured device.

design are the partial noise immunity that differential transmission lines offer and the shielding provided by the ground plane. This shielding could be extended by introducing a second ground plane above the traces but at the cost of increased material.

The cross sectional dimensions are optimized with a two-dimensional transmission line field solver [9]. The following is a description of various competing dimensional effects that were considered. The impedance between the signal traces and ground is proportional to the distance from traces to ground. Additionally, the impedance is proportional to the cross sectional area of the differential traces. The coupling between differential traces diminishes with separation, so in the limit where the differential traces are very far apart, thus minimally coupled, the differential impedance is double the impedance of a single trace. As the distance between differential traces is reduced, the coupling between them grows and charge begins to flow between them, reducing the differential impedance below double that of a single trace [10]. The effect of the width of the ground plane upon the impedance is similar to that of the spacing between the traces: as the ground plane width increases, more conductor is available for the traces to couple to, so the impedance decreases. By this same argument, if the ground plane is cross hatched, less conductor is available for the traces to couple to, so the impedance increases.

2.1. *Dielectric materials*

Two types of dielectric material are compared: an all-polyimide (AP) [7] with dielectric constant of 3.4; and a polyimide–Teflon (TK) composite [8] with dielectric constant of 2.5. Both of these materials are optimized for high speed signal transmission with dielectric constant stability and small loss tangent up to frequencies of order 20 GHz. This range encompasses the range of frequencies of interest for the flex, which is 500 MHz to 2500 MHz. Pure Kapton has been shown [11] to be more radiation hard than Teflon. The radiation tolerance of the all-polyimide dielectric was evaluated for the particular application of the HL-LHC environment.

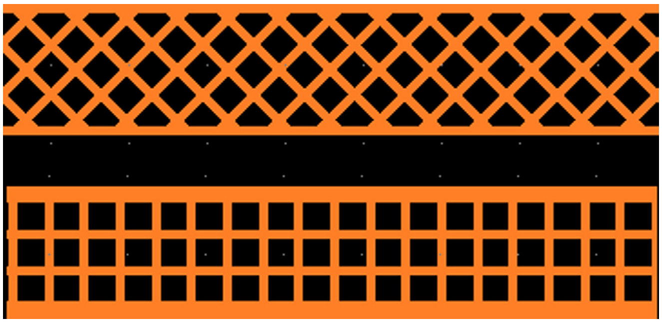

Fig. 2. Diagonal and square cross hatched ground planes.

2.2. *Conductor material*

The conducting material is rolled annealed copper. The rolled annealed process provides a smooth copper surface which reduces skin resistance. The thinnest copper layer available, 16 μm, was chosen to minimize material.

2.3. *Cross hatched ground plane*

The implementation of a cross hatch pattern in the ground plane is a method we have considered which reduces the radiation length, while possibly having an impact on the differential signal quality and electrical characteristics. Two cross hatched designs were examined: a square and a diagonal orientation as shown in Fig. 2. In both cases the mass of the ground plane is reduced by 40% compared to a solid ground plane. Both prototypes have the same external dimensions as the solid ground plane on the 1.0 m AP cable. The square cross hatch is repeated every 457 μm; the diagonal cross hatch, every 650 μm. The area of both hatched patterns is 1.089×10^5 μm^2. Dimensions of the cross hatch are chosen by considering the wavelength of the transmitted signal. The pattern must repeat on a length scale of less than 5% of a wavelength of the transmitted signal [12], which is 6.40 cm for this application, to avoid signal degradation. The width of the copper cross hatch in the ground plane is 127 μm in both designs. The two different styles of ground plane explore whether the return of the common mode signal, carried by the ground plane, is affected by the absence of a straight path. The conclusion of this study is in Section 5.

3. Characterization methods

3.1. *Matching impedance and cable termination schemes*

During electrical measurements, the cables are terminated with 100 Ω impedance adapter boards that have two 50 Ω impedance SMA connectors. To minimize the impedance change at the SMA/adapter board interface, pad widths slim from 1.25 mm to 1.0 mm over a distance of 10 mm to match the diameter of the SMA pins [13]. The cable connects to the adapter board with vias. To minimize the impedance change at these vias, the radius of the through hole is set to 30 gauge and the anti-pad area is maximized with the constraint of not interfering with other vias [14].

3.2. *Bit error rate*

A bit error rate test (BERT) is used to characterize bandwidth through error rate versus frequency. The bit error tester is based on a Xilinx Virtex-4 FPGA board ML405/6. A pseudo-random string of bits is transmitted at a specified frequency through the cable and compared at the receiving end to the original pattern. The