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Research and technical note

Woven ribbon cable for cryogenic instruments

C.R. Cunningham, P.R. Hastings and J.M.D. Strachan

Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK

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Robust woven ribbon cables are described for connecting sensors at low temperatures to higher temperature systems. Woven cables have several advantages over conventional wiring or flat ribbon cables in cryostats: heat sinking is easier; twisted pairs may be used; and miniature multi-way connectors are easily incorporated. Their use is demonstrated in making connections from 131 bolometers in two arrays mounted in a dilution refrigerator at 100 mK. Thermal and electrical properties are discussed, as are other possible applications in cryogenic instruments.

Keywords: ribbon cable; woven cable; cryogenic cable

Thermal loads due to electrical wiring in cryostats are minimized by using low thermal conductivity materials such as constantan, manganin, stainless steel, phosphor-bronze or superconducting alloys, and by ensuring that long, thin wires are used, well heat-sunk to intermediate temperature stages. Unfortunately, such thin wires are fragile and are difficult to handle in large numbers. At the Royal Observatory Edinburgh we are building a submillimetre camera, the Submillimetre Common-User Bolometer Array (SCUBA), for the James Clerk Maxwell Telescope*[1]. It has 131 bolometers operating at 100 mK, cooled using a Kelvinox-25 dilution refrigerator (Oxford Instruments, UK). The major thermal load on the refrigerator mixing chamber is heat flow along the bolometer wiring: each bolometer has a signal and return wire, and bias and monitoring connections add to these to make a total of nearly 300 wires. This number of wires in the system make it essential that the wiring be robust and easily serviced or replaced. Ribbon cables are therefore an attractive option. Warner and Breon[2] describe ribbon cables on Kapton and Goretex substrates and Timbie *et al.*[3] describe ribbon cables made by sandwiching wires between sheets of Kapton. We have developed ribbon cables woven from constantan and Nomex (Du Pont de Nemours International SA, Geneva, Switzerland) fibre, which are robust, easy to heat-sink and allow wire arrangements and materials to be chosen in suitable combinations for particular applications.

* The James Clerk Maxwell Telescope is operated by the Royal Observatories on behalf of the Particle Physics and Astronomy Research Council of the UK, The Netherlands Organisation for Scientific Research and the National Research Council of Canada

Description

The ribbons are woven from 0.2 mm diameter polyurethane-coated constantan (Temple Electrical Co. Ltd, Watford, UK) and Nomex fibre (Woven Electronics Ltd, Salisbury, UK); see *Figures 1* and *2*. The warp consists of alternate strands of wire and Nomex, and the weft (woven) threads are Nomex. Thus the constantan wires are protected from potential short circuits, even if the polyurethane insulation is damaged. The raised parts of the Nomex threads also give some mechanical protection where the ribbon is clamped or glued to a metal surface for heat-sinking. Each signal conductor can be run between earth returns to control capacitance for screening and reducing crosstalk. Wires may be woven in twisted pairs for reduced magnetic field pick-up.

It is important that a complex instrument such as SCUBA can be demounted into assemblies, so connectors are essential. When used with miniature 'D' connectors such as the Cannon 100 way MDM type (ITT Cannon, Basingstoke, UK) each row of connector pins has an associated ribbon cable, enabling the connectors to be crimped and epoxy-potted to the cable, as in *Figure 1*.

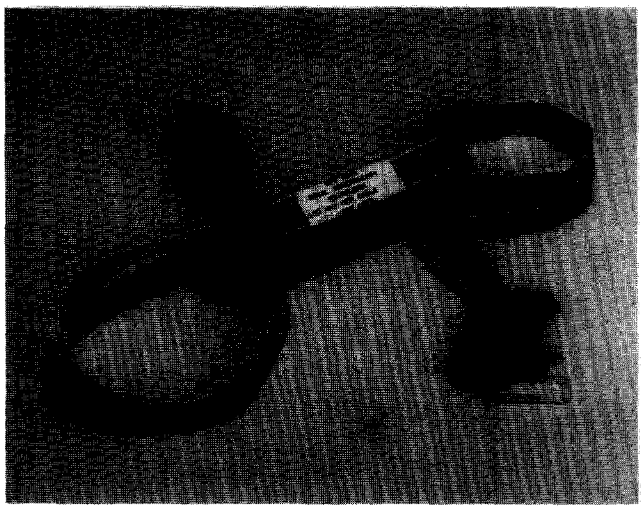

Figure 1 Ribbon cable with connectors

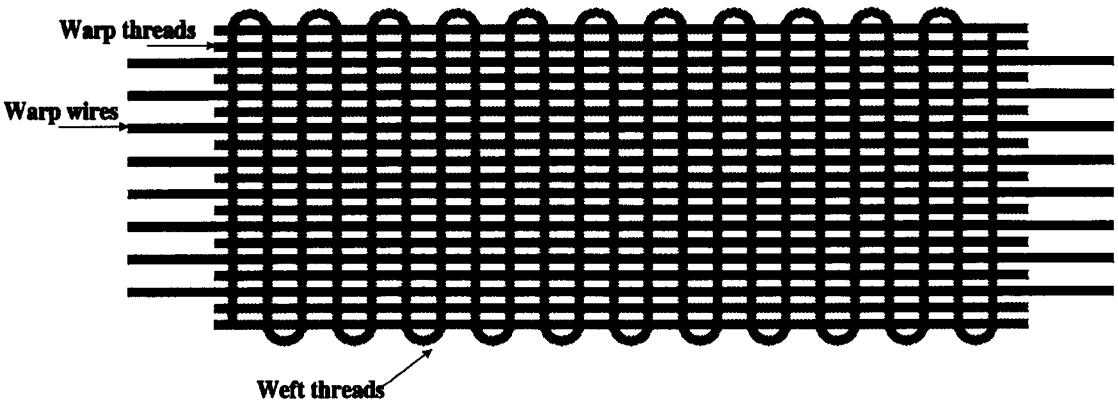

Figure 2 Woven ribbon cable layout

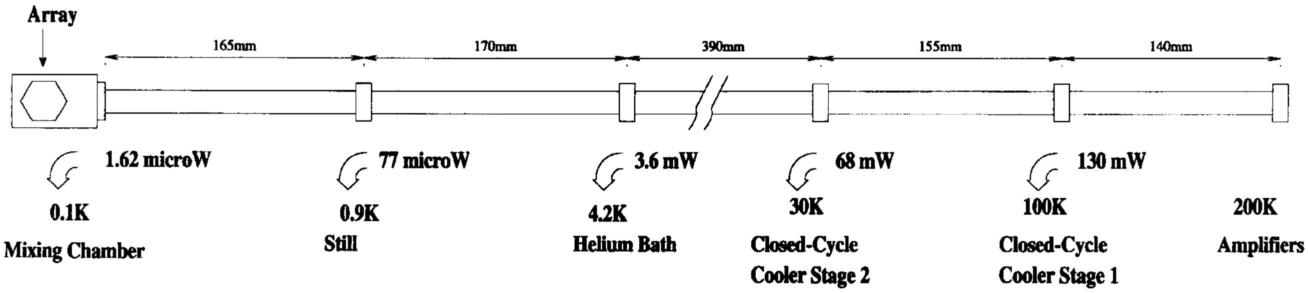

Figure 3 Heat sinks along ribbon cable, with predicted loads due to 312 wires

Heat sinks

It is vital that heat is dumped from a cryogenic cable effectively to avoid excessive thermal leaks. Ribbon cables in SCUBA are used to connect the detectors at 100 mK to amplifiers at 200 K. Heat is dumped at sinks along the cables, as shown in *Figure 3*. The dilution refrigerator used has a cooling power of only 20 μW at 100 mK, so it is vital that heat flow along the cables between the still and the mixing chamber are minimized. Heat sinks formed from a multilayer sandwich of ribbon cable and copper are glued together with epoxy resin, vacuum grease or GE varnish, as in *Figure 4*. Hust[4] shows that the thermal conductivity of the adhesive has little bearing on the efficiency of the heat sink, provided it forms a thin layer (relative to the wire diameter) between the metal and the wire. The Nomex threads protect the wires, reducing the risk of electrical shorts to the metal, and help to ensure that an even, thin layer of adhesive is formed.

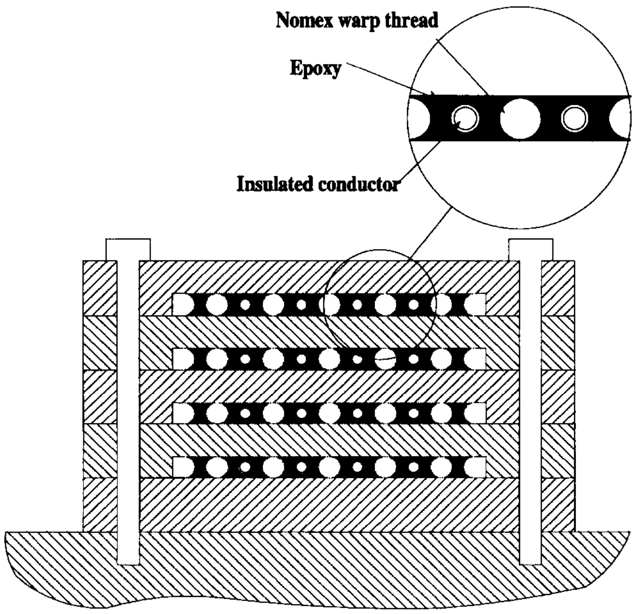

Figure 4 Heat sink cross-section

Electrical properties

Capacitance between adjacent wires is 8 pF per metre, and typical capacitance to a set of copper heat sinks is 34 pF. By using alternate wires as shields connected to signal ground, capacitance between signal wires can be reduced to less than 1 pF. Capacitance between signal wires can be further reduced by weaving the cable so all conductors are flat rather than undulating, and by using shield wires of larger diameter than the signal wires. Woven Electronics have patented techniques available to control impedance for high frequency use. Constantan wires will form thermoelectric junctions where they are connected to copper connectors. In some applications this may be a problem, but not with our bolometer array, where the signals are a.c. coupled.

Thermal load on dilution refrigerator

The three ribbon cables have a total of 312 constantan wires, arranged as three sets of four stacked ribbons, each with 26 conductors (26 is the maximum number of pins in a row on the 100 way MDM connectors). We heat-sink the ribbon cables at 4.2 K on the main ^{4}He bath, at 0.9 K on the still and at 0.1 K on the mixing chamber. Lengths of ribbon between heat sinks are shown in *Figure 3*, as are estimated heat flows to each sink for the case where we assume no thermal resistance at each sink. Thermal conductivity integrals of constantan are calculated from data in reference 5. Nomex warp thread has a thermal conductance about 100 times less than constantan, and so can be ignored.

Estimated thermal loads are given in *Table 1* for three situations:

1 perfect thermal anchoring where the wire temperatures are the same as the sinks;
2 where there is a thermal resistance between the cables and the still so that the wire temperature is raised above the nominal still temperature of 0.9 K; and
3 where there is no sinking to the still.

The arrays, which weigh 3 kg in total, are supported by an AGOT carbon[6] and Vespel SP22 (DuPont (UK) Ltd, Hemel Hempstead) structure, which is similarly heat-sunk to the still. Conductivity data for AGOT carbon[7] and Vespel SP22[8] predict a thermal load of 1.1 μW. If we had perfect heat-sinking, we would expect this load combined with the wiring load to produce a base temperature of 58 mK with a Kelvinox-25 refrigerator, and cooling power of $\approx$17 μW at 100 mK, our operating temperature. In practice, we find that we have only 5 μW cooling power when the mixing chamber is controlled at 100 mK, so the thermal load from the wires and support structure is $\approx$15 μW. The base temperature is actually 78 mK.

We believe the loads are greater than predicted because the heat-sinking to the still is not as good as we might expect. Using data from Lounasmaa[9] for a worst-case epoxy, and assuming an effective cross-sectional width of epoxy equal to the wire diameter and a film thickness of 0.2 mm, a double sided heat sink 10 mm long would have a thermal resistance of 8.3 Km^{-1} W^{-1} at 1 K. This estimate ignores interface effects, so it is reasonable to expect a thermal resistance of the order of tens of Km^{-1} W^{-1}. To reduce the loads on the mixing chamber still further, heat-sinking to the still would need to be improved, or the constantan wire replaced with wire of lower thermal conductivity.

Alternative wire materials

As we saw earlier, thermal loads on our dilution refrigerator are near the practical limit when using constantan wire. We needed to reduce crosstalk and pick-up in our system, by incorporating grounded screening wires between twisted signal pairs. The extra wires needed would take us above the available cooling power, so we have made ribbon cable using superconducting solid core niobium titanium alloy (NbTi) wire (California Fine Wire Co., Grover City, USA and IMI Titanium, Birmingham, UK) with the copper coating etched away. Each ribbon has 13 twisted signal/return pairs of 0.1 mm diameter, and 15 grounded wires of 0.2 mm diameter between signal conductors, to reduce capacitance between signal wires and consequent crosstalk. This arrangement uses 492 wires in total, again arranged as three stacks of four ribbons. The wire is superconducting below 9 K, so the predicted thermal loads (based on thermal conductivity measurements of NbTi made by Olson[10]) are nearly 10 times lower than those from the 312 constantan wires previously used. We use Pyre-ML (DuPont Imaging/Medical, Circleville, OH, USA) polyimide coating as insulation, because it is tougher than the polyurethane insulation used for the constantan ribbons. The ends of the superconducting wire are etched in a hydrofluoric/nitric acid mixture to remove the tenacious oxide layer, and then copper plated[11]. The ribbon is glued to a small printed circuit board (PCB), and the conductors soldered to pads on the board. PCB mounted MDM connectors can then be used, or copper wire used to connect between the PCB and connector solder buckets. The use of a PCB allows the capacitance between signal wires to be controlled right up to the connector. We have also had ribbon cables woven using Lake Shore quad-twisted pair phosphor-bronze wire (Lake Shore Cryotronics, Westerville, OH, USA), and have successfully used this set-up for connections to carbon resistance thermometers.

Conclusions

Woven ribbon cables have many potential uses in cryogenic instruments. Controlled impedance and ease of termination make them attractive for digital applications such as control lines for infrared arrays, and their robustness makes them suitable for space applications or industrial cryostats.

Acknowledgements

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Table 1 Thermal loads on dilution refrigerator as function of wire temperature at still

Condition	Temperature of wires at still heat sink (K)	Thermal load on still (μW)	Thermal resistance to still ($K\,m^{-1}\,W^{-1}$)	Thermal load on mixing chamber at 0.1 K (μW)
Perfect sinking at still	0.9	77	0.0	1.62
With thermal resistance to still	1.0	76	1.3	2.03
With thermal resistance to still	1.3	74	5.4	4.13
With thermal resistance to still	1.5	73	8.2	6.04
With thermal resistance to still	1.7	70	11.4	8.37
With thermal resistance to still	2.0	66	16.7	12.72
With thermal resistance to still	2.1	60	20.0	14.4
No heat sink on still	–	–	–	45

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