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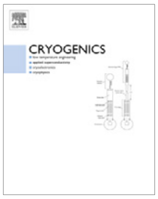

Compact, inexpensive coaxial terminations and wiring for low temperature RF applications

E. Smith [a], R. De Alba [a,*], N. Zhelev [a], R. Bennett [a], V.P. Adiga [a], H.S. Solanki [b], V. Singh [b], M.M. Deshmukh [b], J.M. Parpia [a]

[a] Physics Department, Cornell University, Ithaca, NY 14853, USA
[b] Department of Condensed Matter Physics and Materials Science, Tata Institute of Fundamental Research, Mumbai 400 005, India

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ABSTRACT

We have examined a promising family of radio frequency coaxial connectors (the SSMCX range) suitable for use at low temperatures. We describe the measured characteristics of these connectors in typical arrangements using lossy Cooner stainless steel inner and outer (braided) coaxial cable and other specialty low temperature coaxial cables including Beryllium Copper (BeCu) outer and inner conductors, Copper Nickel (CuNi) outer and Niobium–Titanium (NbTi) superconducting inner conductors, and Nb outer/NbTi inner conductor (homemade) cables. Of these, the BeCu coaxial cable proves to rank among the smallest losses consistently from 300 K down to 4 K. We also characterize Copper, BeCu, and CuNi clad NbTi braided twisted pair "looms", demonstrating that CuNi–NbTi is the most practical choice due to minimal heat leak.

1. Introduction

In recent years, the most widely used miniature RF coaxial cables and connectors incorporated into low temperature research apparatus have seen a dramatic increase in price and also frequent delays in availability. The connectors, commonly known by their former trade name "Microdots" are produced under the Tyco Electronics namebrand [1], and are now designated as Ultra Miniature (LEPRA/CON) RF connectors. Typical prices for bulkhead connectors (part number 141-0002-0002) and mating right angle connector (part number 142-0002-0001) suitable for soldering to a cable currently are $ 35 each. In addition, the functionality of these connectors suffers due to their overly-complicated assembly, which can often leave the connectors shorted (unusable) during construction or after prolonged use. The "competing" line of connectors are of the SSMCX family produced by Molex [2], with equivalent bulkhead connectors (part number 73415-4670) and right angle connector (part number 73413-0070) priced at under $ 5 each. These feature a simplified assembly process, which results in a much higher success rate and increased durability (see Fig. 1 for comparison).

In this paper we describe and test our choice of RF coaxial connectors suitable for wiring of low temperature research apparatus. We also compare RF coaxial lines and "looms", ribbons of 12 twisted pairs of wires suitable for many applications. The combination of these connectors and wiring choices should be both cost-effective and can be a significant time savings in wiring a low temperature apparatus.

Various parameters would dictate the specific choice of cable, including: thermal conductivity, ease of assembly, flexibility so that a cable might be readily connected and heat sunk in tightly constrained cryostats, cost, loss characteristics, and obtainability. For these reasons we have characterized the attenuation of several possible options, ranging from commercially available Beryllium Copper (BeCu), Niobium Titanium (NbTi), Cu, and Stainless Steel coaxial cables, homemade Nb–NbTi coax and various twisted pair looms [3] (including Cu, BeCu, and CuNi clad NbTi). These were all tested at room temperature (∼300 K), as well as liquid Nitrogen (77 K) and liquid Helium (4 K) temperatures with the exception of the Cu twisted pair "loom" which was tested at room temperature only. Ideally, a cryogenic coaxial cable should have minimal attenuation (high electrical conductivity) and a diminishingly small thermal conductivity. Unfortunately, these parameters are coupled (as described by the Wiedemann–Franz Law). The thermal and electrical characteristics of some specially fabricated RF coaxial lines were described some years ago [4,5].

2. Cable assemblies

Six different coaxial cables were tested. The first was a standard 1/32 inch (0.8 mm) diameter BeCu (inner and outer) coax from Micro-Coax (formerly Uniform Tubes) [6]. The second cable was intended for room temperature use and was obtained from Hirose

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[*] Corresponding author.
E-mail address: rd366@cornell.edu (R. De Alba).

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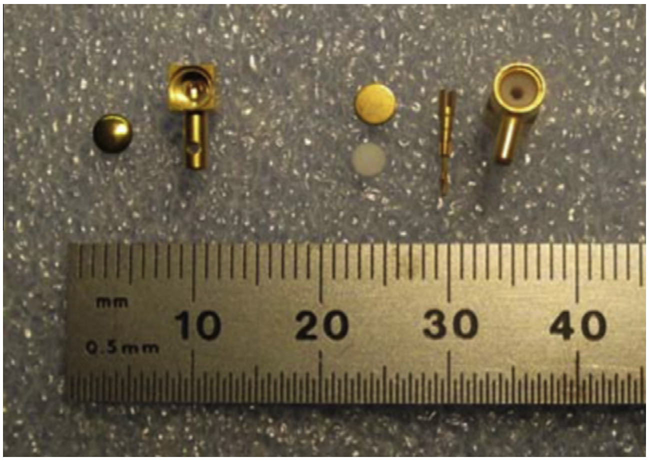

Fig. 1. SSMCX connector assembly (left) and "Microdot" assembly (right) for comparison.

Electric and had Cu inner and outer conductors. The third cable was a homemade superconducting coax, with NbTi inner conductor and Nb outer separated by a Teflon tubing sleeve. A stainless steel (inner and outer braid) coax sold by Cooner Wire [7] and a commercial superconducting coax [8] were also tested. The latter was manufactured by Coax Co. Ltd., with a 0.08 mm diameter NbTi inner conductor and 0.33 mm diameter CuNi outer conductor. In addition, three twisted pair looms were tested. They were purchased from CMR Direct [9], and were fabricated from Cu, BeCu, and CuNi clad NbTi. SSMCX connectors were used to test all cables. Cable details are listed in Table 1.

The commercial superconducting cable (NbTi inner, CuNi outer) had a tendency to kink while attaching connectors. Encasing the cable with 20 gauge Teflon spaghetti helped circumvent this issue, although the assembly remained delicate and difficult to handle. A Cu sleeve was used to bridge the gap between the wire's outer diameter and the SSMCX connector casing. A 2 mm long piece of 0.25 mm i.d. CuNi tubing was crimped onto the inner conductor to facilitate attachment to the connector's inner pin.

A copper sleeve was used when needed in attaching connectors to the outer conductor of the rest of the coaxial cables. The homemade superconducting coax was assembled by vacuum brazing copper sleeves directly onto the ends of the Nb tubing for attachment to the connectors using Nioro® brazing alloy.

Attachment and assembly of SSMCX connectors to these cables involved the use of liquid solder-flux [10] to keep inner and outer conductors in place while heat was applied. For a more detailed account of the connector assembly process (with accompanying photographs) see the Supplementary Material.

The cables tested were chosen based on their utility in broad low-temperature experiments and their availability. Various other combinations of inner/outer conductors have been examined for cryogenic use in the past, including CuNi/stainless steel [11]. Other novel coaxial cable options have been proposed for reduced thermal leakage, such as homemade thin film Cu outer conductors ($\sim$5 μm) [12], but are not tested here.

3. Measurement of attenuation

Attenuation measurements were made using an Agilent 8753ES network analyzer that was connected to the measurement apparatus by a set of cables used to transition from room temperature to 4 K. The attenuation of these extraneous cables and junctions in the setup were characterized by several independent attenuation measurements and were subtracted from the overall attenuation data. The connectors were characterized using all Cu cables, and the results are shown in Fig. 2.

Coaxial lines are usually well modeled by the Telegrapher's equation:

$$\frac{\partial^2}{\partial x^2}V = LC\frac{\partial^2}{\partial t^2}V + (RC + GL)\frac{\partial}{\partial t}V + GRV, \tag{1}$$

where R, L, C are characteristic resistance, inductance, and capacitance of the line per unit length, and G is the conductance of the intermediate dielectric layer. From this, it can easily be shown that if all connections are well matched and reflected signals are negligible, the signal through a coax decays exponentially with length [4]. Attenuation for each cable therefore scales with length, and total attenuation measurements of several cable assemblies can be treated as a system of linear equations to be solved for a single cable as described above.

4. Results

4.1. Connectors

The attenuations of the connectors are displayed in Fig. 2. It is clear that when used with typical cable lengths, the attenuation due to a pair of SSMCX connectors is entirely negligible at room

Table 1
Details of cables tested, including materials, dimensions, and manufacturer. Diameters are listed by manufacturer specification except where noted.

Coaxial cable	Inner conductor	Outer conductor	Dielectric	Inner conductor diam. (mm)	Outer conductor outer diam. (mm)	Manufacturer and product no.
(a) Cu	Cu	Cu	FEP	0.22	0.84	Hirose Electric 1.32
(b) BeCu	Ag plated BeCu	BeCu	PTFE	0.20	0.86	Micro-Coax Special order/UT-034
(c) Homemade S.C.	NbTi	Nb	PTFE	0.31 (measured)	1.02 (measured)	–
(d) Stainless steel	Stainless steel	Stainless steel	PTFE	0.10	0.48	Cooner Wire AS 632–1SS
(e) Commercial S.C.	NbTi	CuNi	PFA	0.08	0.33	Coax Co. Ltd. SC-033/50-NbTi–CN
Twisted pair loom						
(f) Cu	–	–	–	–	–	CMR Direct CMR/CWL-12CU
(g) BeCu	–	–	–	–	–	CMR Direct CMR/CWL-12BC
(h) CuNi clad NbTi	–	–	–	–	–	CMR Direct CMR/CWL-12NT

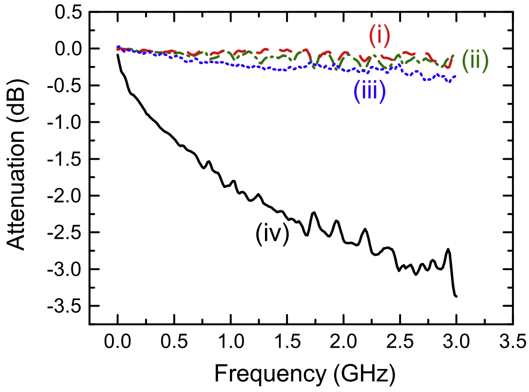

Fig. 2. Attenuation of various SSMCX connectors tested: (i) SMA–SSMCX adapter (Molex 73386-0840), (ii) SSMCX connector pair (Molex 73415-4760 and Molex 73413-0062), (iii) SMA female–female adapter (Connex 132169), and (iv) 1 m Cu coax (for comparison).

temperature. Likewise, an SMA female–female adapter and SMA–SSMCX adapter have attenuations that are an order of magnitude smaller than that of a meter of any coax.

4.2. Coaxial cables

The measured attenuation characteristics are shown in Fig. 3. The BeCu and Cu coax lines have the smallest attenuation for all frequencies at room temperature. The braided Stainless Steel and the commercial superconducting coax have the largest attenuation at room temperature. At 77 K, BeCu and Cu retain their low attenuations. At 4 K, both superconducting cables see a considerable drop in attenuation due to their vanishing resistivities (see Kushino et al. [5] for detailed analysis of superconductivity onset in NbTi coaxes). The homemade superconducting cable provides the smallest attenuation at this temperature. Most attenuation curves show small systematic oscillations at frequencies near 3 GHz. These curious variations are likely due to the formation of standing waves in the lines. This is evidence of a small, but nonzero reflection at cable junctions. Among these coaxial lines, BeCu is most desirable for measurements at a variety of temperatures because of its well-controlled attenuation and low thermal conductivity. The superconducting inner, CuNi outer coax compromises a great deal due to the high resistivity (and fragility) of the outer conductor but could be a useful compromise for primarily low temperature measurements. The performance of our homemade NbTi inner, Nb outer cable at all temperatures is nearly identical to results of previous tests on fully superconducting NbTi inner/outer coaxes [5]. Measurements of cable resistance and capacitance were also taken (for both coaxial cables and twisted pairs), and are given in Table 2.

4.3. Twisted pairs

Results for various twisted pair looms can be seen in Fig. 4. Attenuation is lowest for the Cu pair, as expected. The remaining twisted pairs were comparable in performance to the homemade Nb–NbTi superconducting coax in the frequency range tested, having less attenuation than the stainless steel coax and commercial CuNi–NbTi superconducting coax at room temperature. The attenuation of the CuNi–NbTi twisted pair was lowest at 4 K (due to the superconductivity of NbTi). BeCu results were temperature independent, but the CuNi–NbTi results show a drop in attenuation at 4 K as the NbTi becomes superconducting. Measurements of cross-talk attenuation between neighboring pairs were taken, and showed to be independent of cable type and length. We can thus infer that cross-talk between pairs takes place predominantly at connector sites, with an attenuation of ∼ −30 dB. With respect

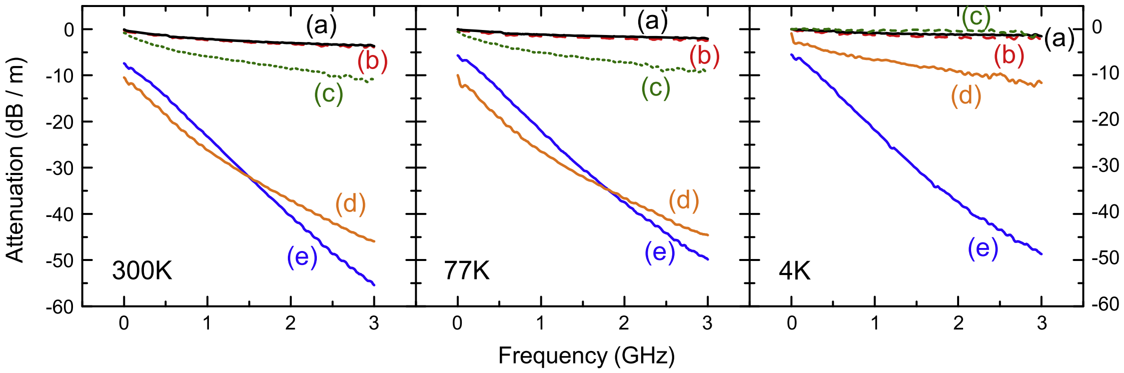

Fig. 3. Attenuation per meter for all coaxial cables tested. The coaxial cables tested were (a) Cu, (b) BeCu, (c) homemade Nb–NbTi superconductor, (d) commercial CuNi–NbTi superconductor, and (e) stainless steel.

Table 2
Upper: Room temperature measurements of coax resistance and capacitance per meter. Lower: Room temperature measurements of twisted pair resistance, pair capacitance, and cross-capacitance between neighboring pairs in a loom.

Cable	Inner cond. DC resistance (Ω/m)	Outer cond. DC resistance (Ω/m)	Capacitance @1 kHz (pF/m)
(a) Cu	1.0	0.2	101
(b) BeCu	2.1	0.5	119
(c) Homemade S.C.	8.2	0.8	101
(d) Commercial S.C.	150	7	97
(e) Stainless steel	102.1	9.6	110
Twisted pair loom conductor	Resistance (Ω/m)	Capacitance of pair @1 kHz (pF/m)	Cross-capacitance @1 kHz (pF/m)
(f) Cu	2.3	55	20
(g) BeCu	12	105	40
(h) CuNi clad NbTi	52	100	35

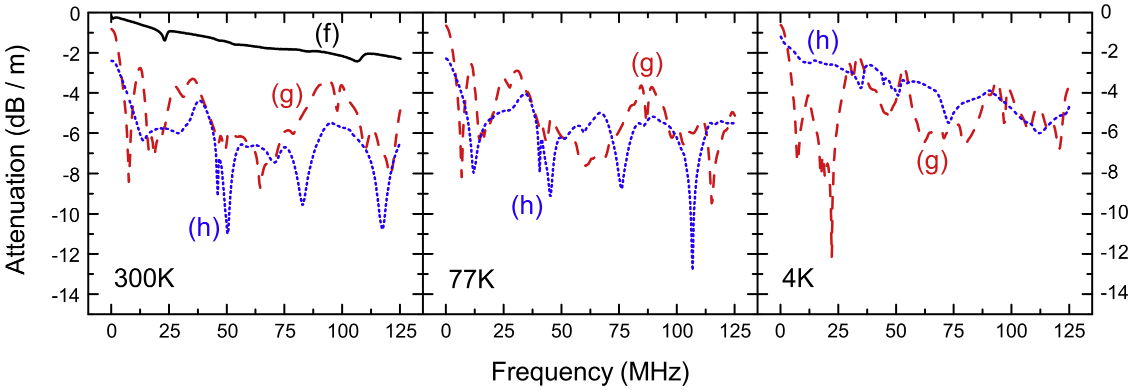

Fig. 4. Typical attenuation per meter of twisted pair looms. The twisted pairs tested were composed of (f) Cu, (g), BeCu, and (h) CuNi clad NbTi. The large semi-periodic variations were dependent on the exact cable configuration that contributed to reflections.

to thermalization of twisted pairs in a dilution refrigerator setting, a calculation invoking the Wiedemann–Franz Law shows that one meter of a BeCu loom (12 twisted pairs) introduces a heat-load of roughly 0.7 nW, and a meter of 12 twisted pair loom of CuNi–NbTi introduces less than 0.1 nW for end temperatures of 50 mK and 5 mK (typical values in a dilution refrigerator). Hence CuNi–NbTi is better for most low-temperature applications. For comparison, a meter of a similar Cu loom results in a heat-load of 400 nW between these temperatures.

5. Discussion

SMA connectors, SSMCX connectors, and SMA–SSMCX adapters exhibit negligible RF signal attenuation, each being at least one order of magnitude smaller than a meter of the best cable measured. Although our homemade Nb–NbTi coaxial cable performed best at helium temperatures, the BeCu cable tested here performed well consistently. It demonstrated minimal RF attenuation at all temperatures tested. This, and its low thermal conductivity, make it ideal for use in low temperature apparatus. The twisted pair looms tested displayed attenuations slightly worse than that of the BeCu coax at all temperatures. However, their compact form factor still makes them highly desirable for many applications. All twisted pair looms showed some degree of cross-talk between neighboring pairs, predominantly at the connector ends. CuNi–NbTi twisted pair looms are best for thermal isolation at low temperatures, producing a smaller heat-load than BeCu for a given temperature gradient.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cryogenics.2012.05.001.

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