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Laser-powered thermoelectric generators operating at cryogenic temperatures

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A thermoelectric generator, operating in a cryostat at liquid helium temperatures, is described. Energy to the generator is supplied via an external laser beam. For this prototype device the associated heat load at permanent operation is comparable with the heat load associated with power delivery via metallic wires. Estimates indicate that still better performance can be enabled with existing thermoelectric materials, thereby far exceeding efficiency of traditional cryostat wiring. We used a prototype generator to produce electric power for measuring critical currents in Nb_3Sn-films at 4 K. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2131202]

Recently, it was noted that crystalline samples of CeB_6 Kondo metal have relatively high values of the figure of merit $ZT \sim 0.2$ at cryogenic temperatures.[1] Here $ZT = TS^2\sigma/k$, where T is the temperature, S is the Seebeck coefficient, and σ and k are electric and thermal conductivities. Using this CeB_6 thermoelectric, we have demonstrated on-demand generation of electric power on a cryogenic platform. There are no wires, but rather energy is being delivered to a cold stage by a laser beam, and converted to electricity by the thermoelectric generator (TEG). Doing this has many advantages including reduction and control over heat input, reduction of noise, and easy external manipulation.

For a TEG the efficiency can be described by the Ioffe expression[2]

$$\eta = \frac{T_1 - T_0}{T_1} \cdot \frac{\sqrt{1 + Z(T_1 + T_0)/2} - 1}{\sqrt{1 + Z(T_1 + T_0)/2} + T_0/T_1} \cdot 100\,\% , \qquad (1)$$

which assumes that Z is not changing much between the cold (T_0) and hot (T_1) ends of the thermoelectric element. In case Z varies, one can use for an estimate the mean value. As Fig. 1 demonstrates for crystals studied,[1] the expected values of η can be as high as 3% at $\Delta T = T_1 - T_0 = 5$ K at ambient liquid helium temperatures ($T_0 \sim 4$ K).

For prototyping a laser-powered TEG (Fig. 2) we use a $\langle 110 \rangle$ oriented CeB_6 crystal 8.1 mm × 1.46 mm × 0.93 mm in size.[1,3,4] The sample is attached to a quartz holder by a metallic indium pad. This holder is placed on a copper base and serves as a heat sink. The circuit consists of a superconducting Nb_3Sn foil (critical temperature $T_c = 18$ K), connecting the opposite ends of the CeB_6 crystal via thin copper wires and rubbed-in In pads. The geometry of the SC foil is constrained such that its critical current equals approximately the maximum current generated by the TEG. The resistance of the crystal (several mΩ) constitutes the internal resistance (r) of the TEG, while the resistance of the attached circuit can be considered as a load resistance. The expression (1) is an optimization for $R_{load} = r$ case.

We excite the TEG by applying a diode laser ($\lambda = 640$ nm), or, sometimes, by resistive heating. The resistive heater is arranged directly on the free end of the crystal. The laser beam enters through a cryostat window and hits an absorption cup mounted on the opposite surface of the crystal. A differential copper-constantan thermocouple is used to measure $\Delta T = T_1 - T_0$. The absorbed radiation power W_h has been determined comparing ΔT_{laser} with the $\Delta T_{resistive\ heater}$. The measurements were carried out at ambient temperatures $T_0 = 3.5-6.5$ K, in the ST405 "CRYOMECH" cryostat. The absolute accuracy of measurements is about 10%.

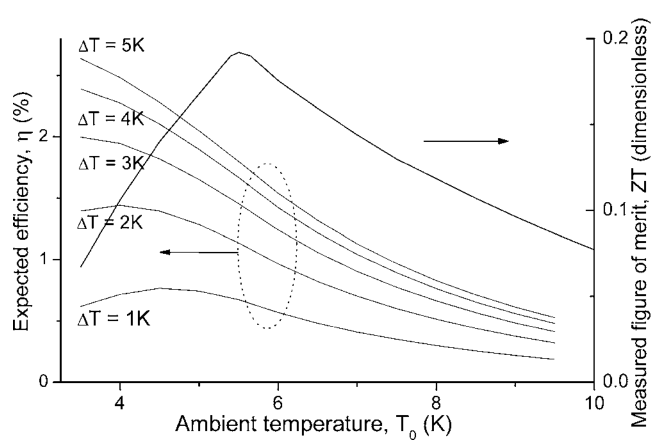

FIG. 1. Generator efficiency corresponding to Eq. (1) based on the values of ZT from the previous report (see Ref. 1).

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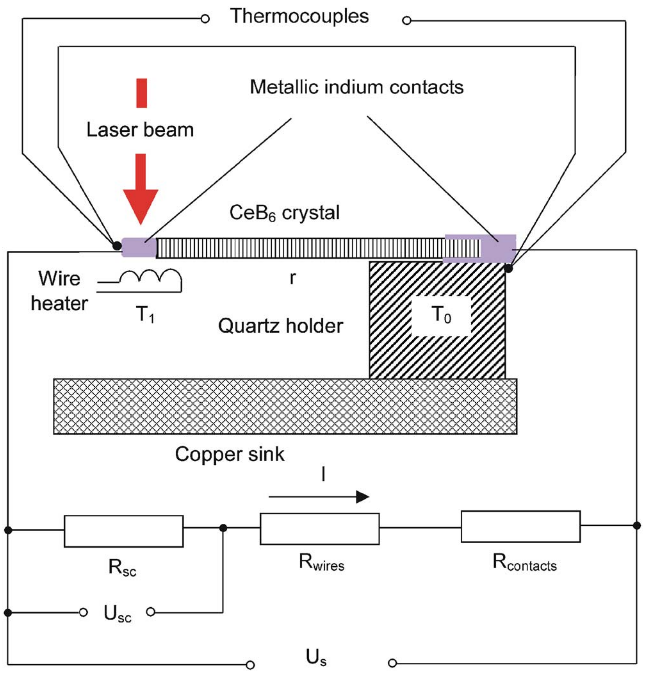

FIG. 2. (Color online) Schematic of the generator experiment.

The quantitative performance of the TEG is characterized by using its power to transition superconducting films to the normal state. Comparing critical currents for the superconducting foil determined in the open-circuit *I-V* mode (when the current is applied externally) with the critical current of the closed circuit (when the current is generated by the Seebeck effect), we determine the generated current. Special care is taken to correct for an additional contact resistance ($\sim$0.5 mΩ) in case of the closed circuit. The *I-V* calibration of superconducting foil is performed in the open-circuit mode for all the values of the external heating power W_h and ambient temperatures T_0, which subsequently were used for closed-circuit measurements. The generated current as a function of applied heating is shown in Fig. 3. As expected, the maximal current ($I\sim 43.6$ mA) corresponds to the minimal load ($\sim$1 mΩ). When the current is high enough, the foil goes to the normal state and the load resistance grows. Thus, R_{load} depends on the W_h as well as on T_0. Meanwhile, the intrinsic resistance r also depends on T and drops in the vicinity of T_0 (Kondo effect) when the temperature increases. As a result, $R_{\text{load}}\sim 3.5$ mΩ is optimal at small

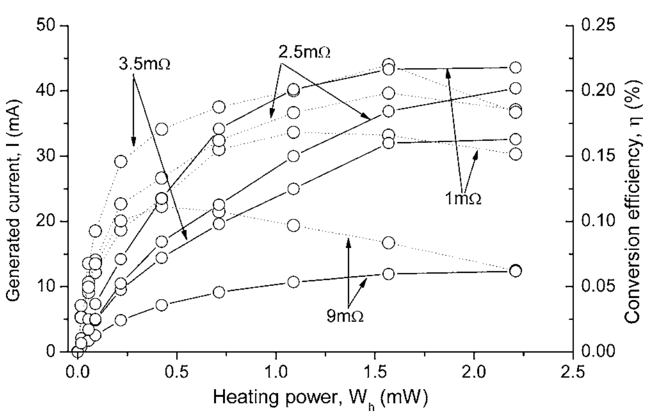

FIG. 3. Generated current (solid lines) and efficiency (dotted lines) at different values of external resistive loads and ambient temperature 3.5 K.

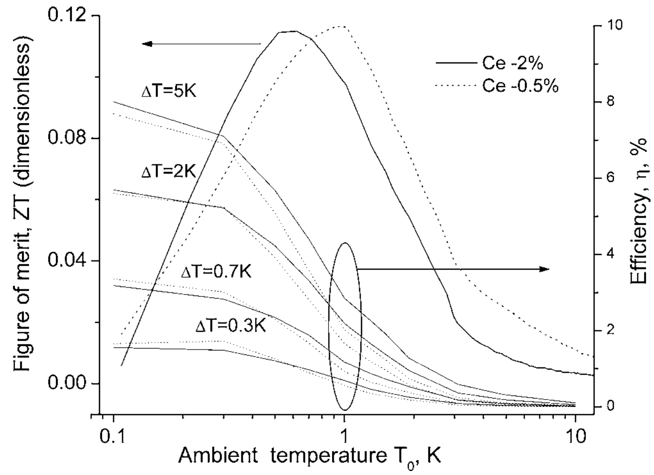

FIG. 4. Efficiency and figure of merit for $La_{1-x}Ce_xB_6$ crystals (at $x=0.02$ and 0.005) of prospective thermoelectric generators.

powers W_h. At higher W_h optimal R_{load} is smaller. The maximal output ($\sim$4.1 μW) is generated at $R_{\text{load}}\sim 2.5$ mΩ at the ambient temperature $T_0=3.5$ K.

The efficiency of heat release from the crystal to the heat sink is essential to determining TEG efficiency. Given the 0.5 mΩ contact resistance, the thermal conductivity is $\sim$0.55 mW cm^{-1} K^{-1}, which is less than the thermal conductivity of the crystal at least a factor of 10. For this reason, at large heat loads there is a large temperature difference between the cold end and the heat sink. As a result, the operational range of the TEG shifts to a non optimal $ZT(T)$ regime. This reduces the device efficiency. The values $\eta=(W_R/W_h)\times 100\%$ are plotted in Fig. 3. Here $W_R=I^2\times R_{\text{load}}$. The maximum value of $\eta\sim 0.22\%$ is reached at $R_{\text{load}}\sim 3.5$ mΩ at $W_h=1.57$ mW and $T_0=3.5$ K. Note the applied heat load W_h is not the absorbed heat load W_a. This value for the given case can be estimated as $W_a\sim 640$ μW, hence, parasitic losses (heat flow via contact wires, thermocouple, superconducting foil, etc.) are huge. In accordance with the equation $V=S\Delta T=I(R+r)$, the Seebeck voltage is $V\sim 200$ μV which corresponds to $\Delta T\sim 2$ K at the $R_{\text{load}}=3.5$ mΩ. Since the temperature of the hot end is $\sim$8.5 K, the temperature of the cold end is $\sim$6.5 K rather than 3.5 K. Correspondingly, it follows $\eta\sim 0.55\%$ for the efficiency defined as $\eta=(W_R/W_a)\times 100\%$. This value corresponds well to the theoretical estimate $\sim$0.7%, which follows from Eq. (1) at $ZT\sim 0.12$—which is the average value near $T=7.5\pm 1$ K.

In practice, higher values of efficiency close to the theoretical limits are achievable at higher values of ΔT, which is possible if the sample has an optimal geometry (a thin rod with a large base) to allow the required heat outflow. Also, parasitic heat losses should be minimized. Of course, it is better to work with the higher values of *ZT*. It should be noticed in this respect that there are published data on CeB_6 crystal[5] with values of the Seebeck coefficient twice as large as ours. Such crystals, provided σ/k is as high as ours, can quadruple TEG efficiency.

Another interesting opportunity is related to the Kondo crystals $La_{1-x}Ce_xB_6$ at $x\sim 0.01$ (Ref. 6) with values of $S\sim 100$ μV/K at $T\sim 0.3$–0.8 K.[7] We measured heat and electric conductivity of these crystals[8] to make sure that $k/\sigma T$ reaches the Lorenz number $L_0\sim 25$ nW Ω/K^2 below

4 K temperatures, so that one can plot the figure of merit $ZT(T)$ (Fig. 4). Relying on this curve and the Eq. (1), efficiencies ~10% and higher could be achieved at 0.3 K ambient temperatures.

In conclusion, we have demonstrated that thermoelectric materials can supply electric power at cryogenic temperatures, with power supplied by laser beams. No wiring is required. The estimates show that at efficiencies better than 0.5% thermoelectric generators provide better performance in terms of the *heat load/electric current* than existing metallic wire solutions.[9] We reached this limit, and it can clearly be surpassed by existing technologies. Note, that one can also activate different circuits by switching on the corresponding generator in multiple beam/generator arrangement. The laser delivery of electric power can be performed selectively in time (on demand), so that there is no permanent heat load to the cold finger of the cryostat. It may be essential in cases when the long cryogenic lifetimes are mandatory, for example, in space-based applications, and a permanent power supply is not required.

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[9]The authors are grateful to Dr. A. Kadin who outlined this point to them.